SIMULATION OF NITROGEN LIQUEFICATION CYCLES

A PROJECT REPORT SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology
in
Thermal Engineering

by

SHAILESH PRASAD
Roll-207ME313

Department of Mechanical Engineering
National Institute of Technology
Rourkela
2008-2009

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Under The Guidance of
Prof. Sunil Kumar Sarangi

Department of Mechanical Engineering
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Dedicated to
my
mom & dad

National Institute of Technology, Rourkela

CERTIFICATE

This is to certify that the thesis entitled, **"simulation of nitrogen liquefication cycles"** submitted by **Shailesh Prasad** in partial fulfillment of the requirements for the award of MASTER OF TECHNOLOGY Degree in **Mechanical Engineering** with specialization in **"Thermal Engineering"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

Date:

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CONTENTS

Abstract

System simulation is the calculation of operating variables such as pressure, temperature and flow rates of energy and fluids in a thermal system operating in a steady state. The equations for performance characteristics of the components and thermodynamic properties along with energy and mass balance form a set of simultaneous equations relating the operating variables. The mathematical description of system simulation is that of solving these set of simultaneous equations which may be non-linear in nature. Simulation is not needed in design conditions because in the design process the Engineer probably chooses reasonable values of the operating variables and selects the components that correspond to operating variables.

Cryogenics is the branch of engineering that is applied to very low temperature refrigeration applications such as in liquefaction of gases and in the study of physical phenomenon at temperature of absolute zero. The various cryogenic cycles as Linde cycle, Claude's cycle , Stirling cycle etc govern the liquefaction of various industrial gases as Nitrogen, Helium etc. We have the operating conditions and operating variables which can be solved numerically which is tedious. The following work aims to simulate the nitrogen liquefication cycles with the help of the simulation tool ASPEN HYSYS where all calculations are done at steady state and the results hence obtained.

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Nomenclature

$\dot{m}$ = mass flow rate
$\dot{Q}$ = heat transfer

$\dot{W}$ = work transfer

$\dot{m}_f$ = liquid mass flow rate

T = temperature

y = yield

ε = effectiveness

C = heat capacity rate

p = pressure

v = volume

R= universal gas constant

Geek Symbols

ρ = density

γ = adiabatic index

Subscripts

C= cold fluid

h = hot fluid

Abbreviations

HX = heat exchanger

CHAPTER: 1

INTRODUCTION

1.1 Gas liquefaction systems

Liquefaction of gases includes a number of phases used to convert a gas into a liquid state. The processes are used for scientific, industrial and commercial purposes. Many gases can be put into a liquid state at normal atmospheric pressure by simple cooling; a few, such as carbon dioxide, require pressurization as well. Liquefaction is used for analyzing the fundamental properties of gas molecules (intermolecular forces), for storage of gases, for example: LPG, and in refrigeration and air conditioning. There the gas is liquefied in the condenser, where the heat of vaporization is released, and evaporated in the evaporator, where the heat of vaporization is absorbed. Ammonia was the first such refrigerant, but it has been replaced by compounds derived from petroleum and halogens.

Liquid oxygen is provided to hospitals for conversion to gas for patients suffering from breathing problems, and liquid nitrogen is used by dermatologists and by inseminators to freeze semen. Liquefied chlorine is transported for eventual solution in water, after which it is used for water purification, sanitation of industrial waste, sewage and swimming pools, bleaching of pulp and textiles and manufacture of carbon tetrachloride, glycol and numerous other organic compounds.

Liquefaction of helium (^4He) with the Hampson-Linde cycle led to a Nobel Prize for Heike Kamerlingh Onnes in 1913. At ambient pressure the boiling point of liquefied helium is 4.22 K (-268.93°C). Below 2.17 K liquid ^4He has many amazing properties, such as climbing the walls of the vessel, exhibiting zero viscosity, and offering no lift to a wing past which it flows.

The liquefaction of gases is a complicated process that uses various compressions and expansions to achieve high pressures and very low temperatures; using for example turbo expanders. The liquefaction of air is used to obtain nitrogen, oxygen and argon by separating the air components by distillation.

This chapter discusses several of the systems used to liquefy the cryogenic fluids. We shall be concerned with the performance of the various systems, where performance is specified by the system performance parameters or payoff functions.

1.2 System performance parameters

There are three payoff functions we might use to indicate the performance of the liquefaction systems:

1. Work required per unit mass of gas compressed ,
2. Work required per unit mass of gas liquefied ,
3. Fraction of the total flow of gas that is liquefied.

1.3 Refrigeration Efficiency

It is desirable to have a method of comparing real refrigerators with the ideal refrigerator. It is of intrest to know the maximum efficiency that can be achieved by such an engine operating between two reservoir at different temperatures. The French engineer Carnot describe an engine operating in particularly simple cycle knows as Carnot cycle.

The performance of real refrigerator is measured by the coefficient of performance (COP), which is define as the ration of refrigeration effect to the work input, the inverse of the efficiency term.

Thus,

$$\mathrm{COP} = \frac{\text{heat absorbed from low−temperature source}}{\text{net work input}} = \frac{Q}{W} \tag{1.1}$$

The figure of merit (FOM) is still another means of comparing the performance of practical refrigeration and is define as

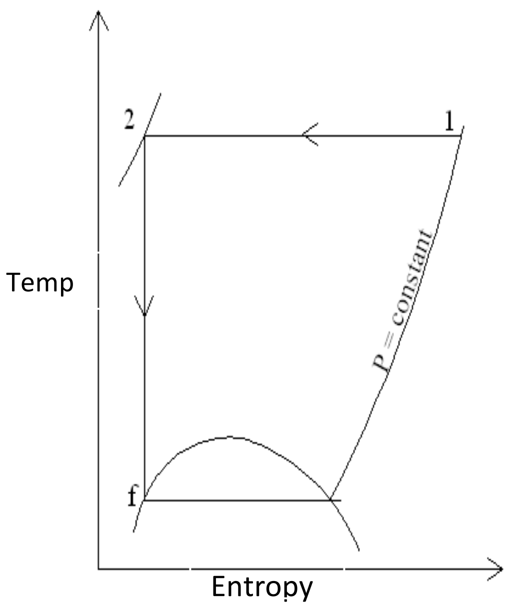
$$\mathrm{FOM} = \frac{\mathrm{COP}}{\mathrm{COP_{ideal}}} = \frac{\mathrm{COP}}{\mathrm{COP_{carnot}}}$$

Where COP is the coefficient of performance of the actual refrigerator system and $\mathrm{COP_{ideal}}$ and $\mathrm{COP_{carnot}}$ is the coefficient of performance of the thermodynamically ideal system and Carnot refrigerator, respectively. The figure of merit for a liquefier is generally written as

$$\mathrm{FOM} = \frac{W_i/\dot{m}}{W/\dot{m}_f}$$

1.4 The thermodynamically ideal system

In order to have a means of comparison of liquefaction systems through the figure of merit, we shall first analyze the thermodynamically ideal liquefaction system. This system is ideal in the thermodynamic sense, but it is not ideal as far as practical system is concerned. The perfect cycle in thermodynamics is the Carnot cycle. Liquefaction is essentially an open system process, therefore for an ideal liquefaction we shall choose the first two processes in the Carnot cycle; a reversible isothermal compression followed by a reversible isentropic expansion. The gas to be liquefied is compressed reversibly and isothermally from ambient conditions to some high pressure. This high pressure is selected so that gas will become saturated liquid upon reversible isentropic expansion through the expander. The final condition is taken as the same pressure as the initial pressure. The pressure attained at the end of isothermal compression is extremely high in the order of 70Gpa and it is highly impracticable to attain this pressure in a liquefaction system, which is the reason it is not an ideal process for a practicable system.



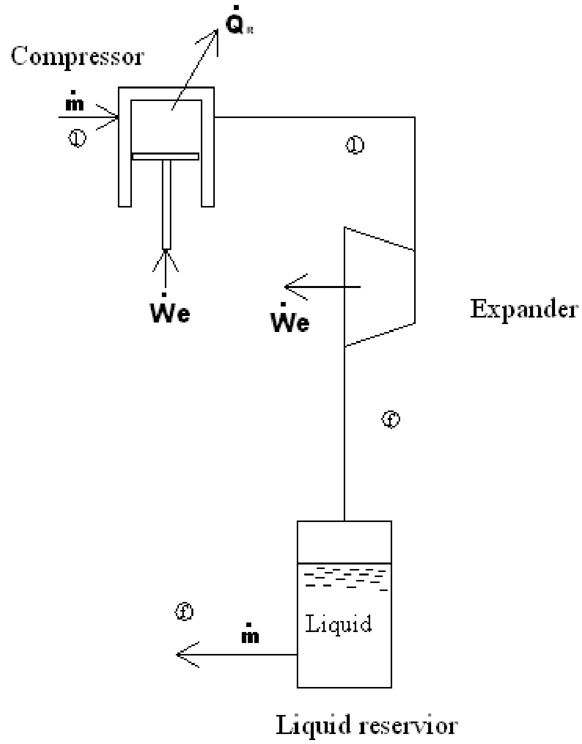


Figure: 1.1 The thermodynamically ideal liquefication system

(a) Thermodynamic cycle T-S plane, (b) Apparatus setup

The First law of thermodynamic for steady flow may be written as:

$$\dot{Q}_{net} - \dot{W}_{net} = \sum_{outlet} \dot{m}h - \sum_{inlet} \dot{m}h \tag{1.1}$$

Applying the First law to the system shown in figure:

$$\dot{Q}_R - \dot{W}_1 = \dot{m}(h_f-h_1) = - \dot{m}(h_1-h_f) \tag{1.2}$$

The heat transfer process is reversible and isothermal in the Carnot cycle. Thus, from the second law of Thermodynamics

$$\dot{Q}_{R} = \dot{m}T_1 (s_2\text{-}s_1) = - \dot{m}T_1 (s_1\text{-}s_f) \qquad (1.3)$$

Because of process form point 2 to f is isentropic, $\mathbf{s_1=s_f}$ where **s** is the entropy of the fluid. Substituting $\dot{Q}_R$ from equation (1.3) into equation (1.2) we may determine the work requirement for the ideal system.

$$-\frac{\dot{W}\iota}{\dot{m}} = T1\ (s_1\text{-}s_f) - (h_1\text{-}h_f) \qquad (1.4)$$

1.5 Production of low temperatures

Joule Thompson effect

Most of the practical liquefaction systems utilize an expansion valve or a Joule Thomson valve to produce low temperatures. If we apply the first law for steady flow to the expansion valve, for zero heat transfer and zero work transfer and for negligible kinetic and potential changes, we fine h1= h2 .Although the flow within the valve is irreversible and is not an isenthalpic process, the inlet and the outlet do lie on the same enthalpy curve. We note that there is a region in which an expansion through the valve produces an increase in temperature, while in another region the expansion results in a decrease in temperature. Obviously we should operate the expansion valve in a liquefaction system in the region where there is a net decrease in temperature results. The curve that separates two regions is called the *inversion curve*. The effect of change in temperature for an isenthalpic change in pressure is represented by the *Joule-Thompson coefficient*.

Adiabatic expansion

The second method of producing low temperatures is the adiabatic expansion of the gas through a work producing device, such as an expansion engine. In the ideal case, the expansion would be reversible and adiabatic and therefore isentropic. In this case we can define the isentropic coefficient which expresses the temperature change due to a pressure change at constant entropy.

Existing Gas liquefaction systems

Of the various gas liquefaction techniques developed by various cryogenic experts, some of them are listed below:-

1: Simple Linde Hampson system

2: Precooled Linde Hampson system

3: Linde dual pressure system

4: Cascade system

5: The Claude system

6: The Kaptiza system

7: The Collins liquefaction system

CHAPTER: 2

LITERATURE SURVEY

2.1 Simple Linde-Hampson system

The Linde-Hampson system was the second used to liquefy gases (the cascade system was the first), although it is the simplest of all the liquefication system is show in figure 2.1 and cycle is show in T-S plane in figure2.2

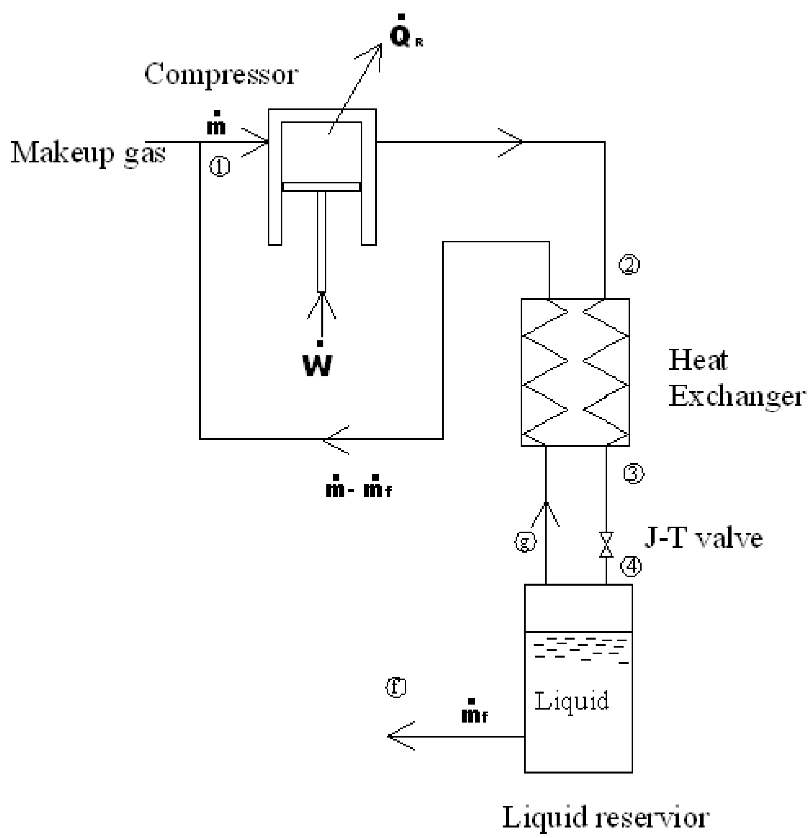


Fig: 2.1 Linde-Hampson liquefication system

A basic differentiation between the various refrigeration cycles lies in the expansion device. This may be either an expansion engine like expansion turbine or reciprocating expansion engine or a throttling valve. The expansion engine approaches an isentropic process and the valve an isenthalpic process. Isentropic expansion implies an adiabatic reversible process while isenthalpic expansions are irreversible. In the Linde system, the basic principle of isenthalpic expansion is also incorporated where as in Claude’s cycle involves both isentropic and isenthalpic expansion procedure.

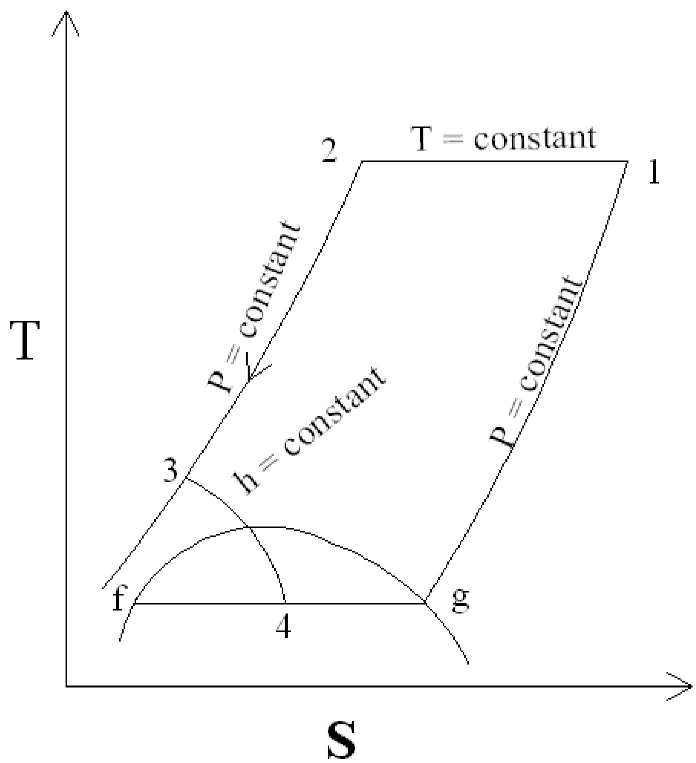


Fig: 2.2 Linde-Hampson liquefication cycle (T-S plot)

2.1.1 Working principle

The air enters the compressor through air pump which forced into compressor and compressed thereby being heated. The heat is removed in the cooling apparatus may be air cooled or water cooled and the compressed air finally reach to ambient temperature. Then it pass through counter flow heat exchanger where it temperature decrease below inversion temperature of working fluid. The air therefore reaches the J-T valve so that it expand through valve , so that it constantly falling in temperature, reaches at lower and lower temperature and eventually the critical temperature of the liquid air is reached and liquid air begins to collect in chamber .

2.1.2 Performance of system

In order to analyze the performance of the system, let us assume ideal condition: no irreversible pressure drops (except for the expansion valve), no heat inleak from ambient conditions, and 100 percent effective heat exchanger.

Applying the first law for steady flow to the combine heat exchanger, expansion valve, and liquid receiver, we obtain

$$0 = (\dot{m}-\dot{m}_f)\, h_1 + \dot{m}_f h_f - \dot{m} h_2 \qquad (4.1)$$

Solving for the fraction of the gas flow that is liquefied

$$\frac{\dot{m}}{\dot{m}} = y = \frac{h1-h2}{h1-hf} \qquad (4.2)$$

The fraction of gas liquefied (the liquid yield) thus depend upon:

1) The pressure and temperature at ambient condition (point 1), which fix h_1 and h_f
2) The pressure after the isothermal compression, which determines h_2 because the temperature at state points 2 is specified by the temperature at point 1

2.2 Claude system

The expansion through an expansion valve is an irreversible process, thermodynamically speaking. Thus if we wish to approach closer to the ideal performance, we must a better process to produce low temperatures. In the Claude system, energy is removed from the gas stream by allowing it to do some work in an expansion engine or expander. The Claude cycle is shown in figure2.3

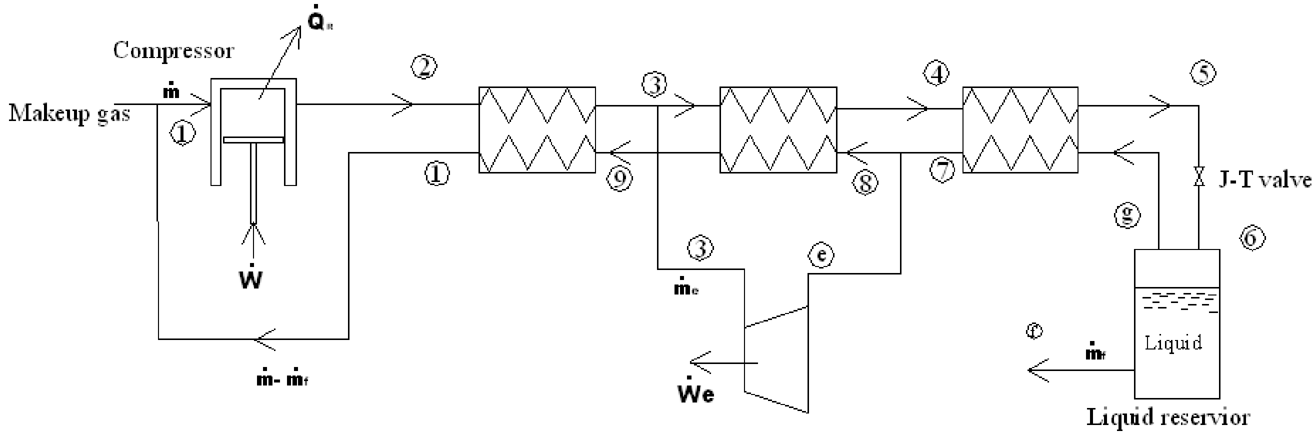


Fig: 2.3. The Claude system

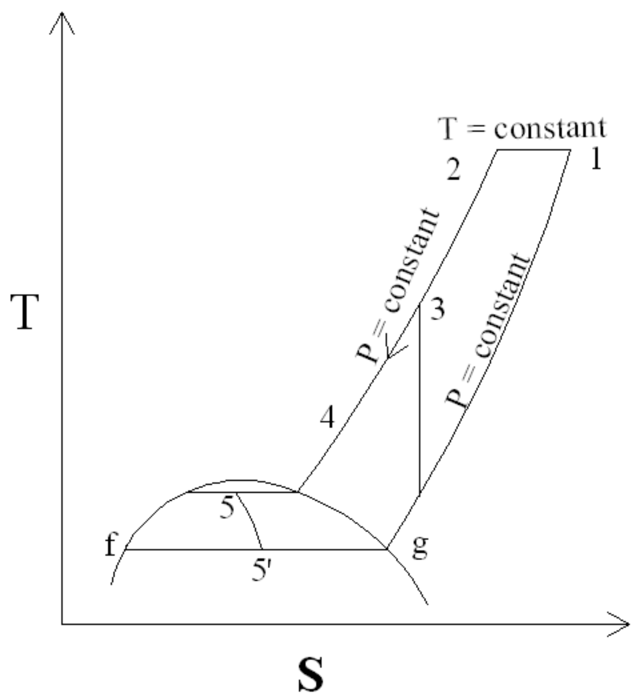


Fig: 2.4 Claude cycle (T-S) plane

An expansion valve is still necessary in the Claude system because much liquid cannot be tolerated in the expander in the actual system. The liquid has much compressibility than the gas, therefore, if liquid were formed in the cylinder of an expansion engine (positive displacement type), high momentary stress would result. Some rotary turbine expanders (axial-flow type) have developed that can tolerate as much as 15% liquid by weight without damage to the turbine blade

In some Claude systems, the energy output of the expander is used to help compress the gas to be liquefied. In most small scale system, the energy is dissipated in the brake or in an external air blower .whether the energy is wasted or not does not affect the liquid yield; however, it does increase the compression work requirement when the expander work is not used

2.2.1 Performance of system

Applying the first law for steady flow to the heat exchangers, the expansion valve, and liquid receiver as a unit, for no external heat transfer

$$0 = (\dot{m}-\dot{m}_f)\, h_1 + \dot{m}_f h_f + \dot{m}_e h_e - \dot{m} h_2 - \dot{m}_e h_3 \qquad (5.1)$$

If we define the fraction of the total flow passes through the expander as *x*, or

$$x = \frac{\dot{m}e}{\dot{m}} \qquad (5.2)$$

Then liquid yield can be obtain form equation (5.1) as

$$\frac{\dot{m}f}{\dot{m}} = y = \frac{h1-h2}{h1-hf} + x\ \frac{h3-he}{h1-hf} \qquad (5.3)$$

Again we see that the second term represent the improvement in performance over the simple Linde-Hampson system.

The work requirement per unit mass compressed is exactly the same as that of the Linde-Hampson system if the expander work is not utilized to help in the compression. If the expander work is used to aid in the compression, then the net work requirement is given by

$$-\frac{\dot{W}}{\dot{m}} = -\frac{\dot{W}c}{\dot{m}} - \frac{\dot{W}e}{\dot{m}} \tag{5.4}$$

Applying the first law for steady flow to the expander, we obtain the work expression

$$\dot{W}_e = \dot{m}\ (h_{3-}\ h_e) \tag{5.5}$$

If the expander work is utilize to aid I compression, the net work is given by

$$-\frac{\dot{W}}{\dot{m}} = [T_1\ (s_1\text{-}s_2) - (h_1\text{-}h_2)] - x\ (h_3\text{-}h_e) \tag{5.6}$$

In claude system of 3 heat exchanger setup we can find that there is phase change in second and thirds heat exchanger so that we can apply effectiveness term directly , only first heat exchanger have freedom to use effectiveness and minimum temperature approach to solve it, so effectiveness of heat exchanger is define as:

"The ratio of the actual heat transfer to the heat transfer attainable in an infinitely long counter flow exchanger"

$$\varepsilon = \frac{Cc(Tc_{out} - Tc_{in})}{Cmin(Th_{in} - Tc_{in})} = \frac{Ch(Th_{in} - Th_{out})}{Cmin(Th_{in} - Tc_{in})} \tag{5.7}$$

2.3 The Kapitza system

Kapitza (1939) modified the basic Claude system by eliminating the third heat exchanger or low temperature heat exchanger. Several notable practical modifications were also introduced in this system a rotary expansion engine was instead of reciprocating expander. The first or high temperature heat exchanger in the kapitza system was actually a set of valved regenerators, which combined the cooling process with the purification process. The incoming warm gas was cooled in one unit and impurities were deposited there, while the outgoing stream warmed up in the other unit and flushed out the frozen impurities deposited in it.

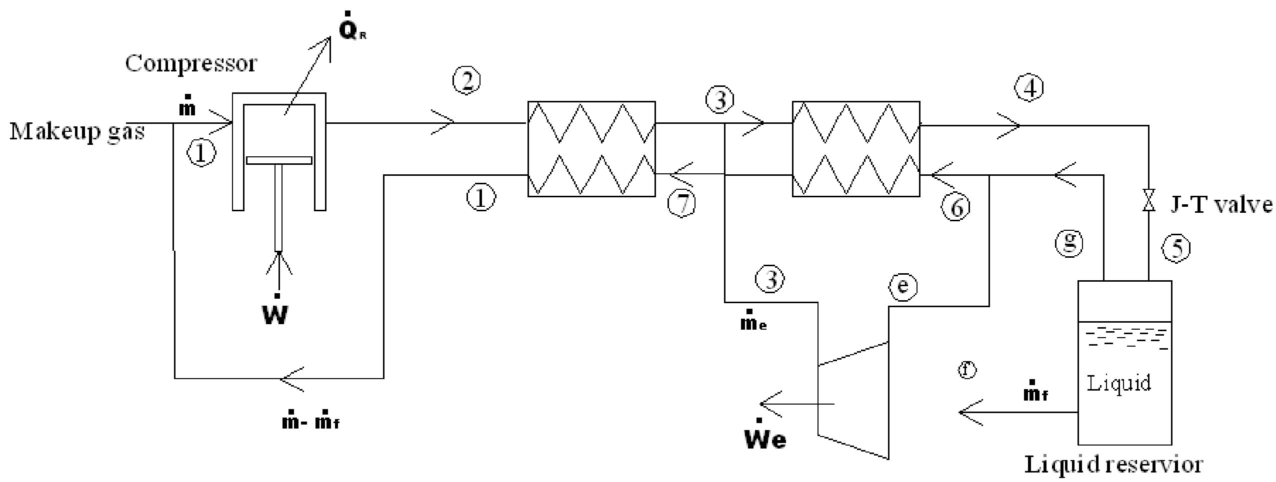


Fig: 2.5. The Kapitza system

2.4 The Haylent system

Helandt (Davies 1949) noted that for high pressure of approximately 20Mpa (200 atm) and an expansion engine flow ratio of approximately 0.60, the optimum value of temperature before expansion through the expander was nearly ambient temperature. Thus one could eliminate the first heat exchanger in Claude system by compressing the gas to 200 Mpa. Such a modified

Claude system is called the Heylandt system after its originator, and is use extensively in high-pressure liquefication plant for air

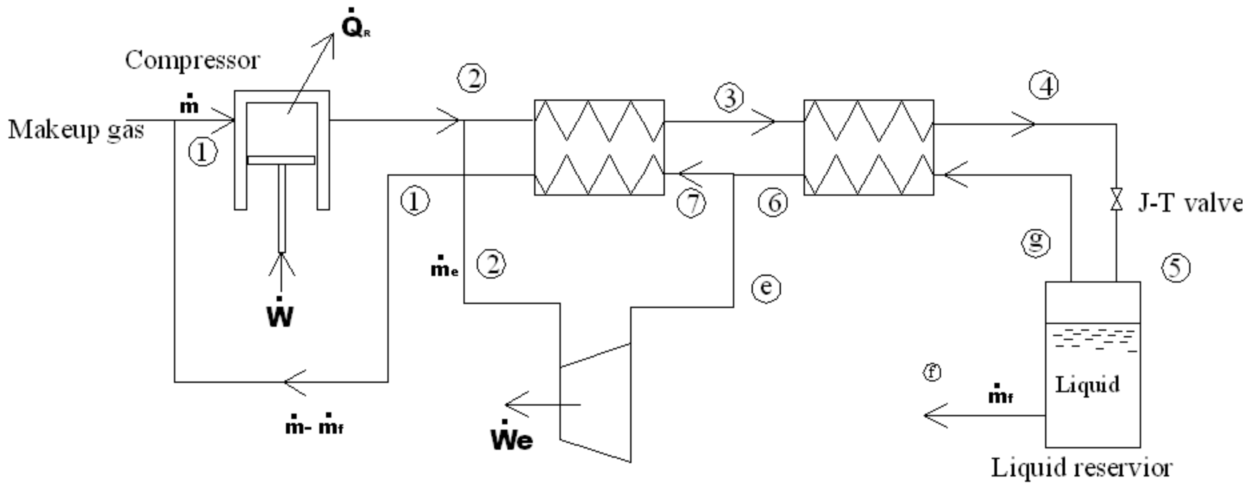


Fig: 2.6. The Haylent system

Chapter: 3

ASPEN-One

3. AspenONE

3.1 Introduction

aspenONE is AspenTech's comprehensive set of software solutions and professional services designed to help process companies achieve their operational excellence objectives. It leverages the value of simulation models to help process companies increase operational efficiency and profitability across their global enterprise. Aspen-one cover four major field as shown in figure:2.1 , Chemical , Energy , Polymer , Pharmaceuticals.

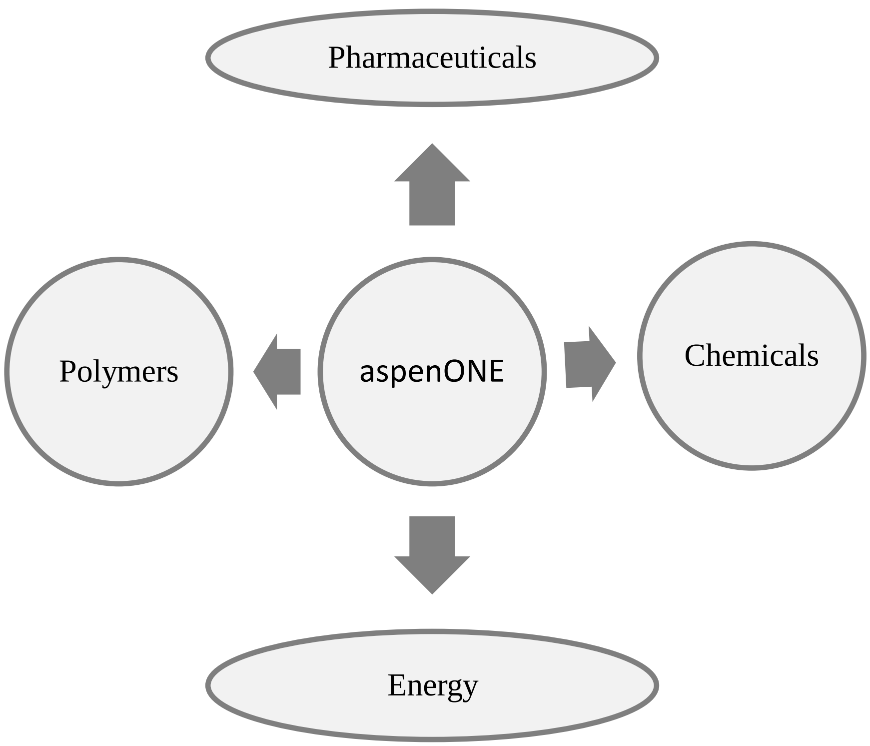


Fig: 3.1 Industries and Business Areas of aspenONE

3.2 Aspen-ONE engineering

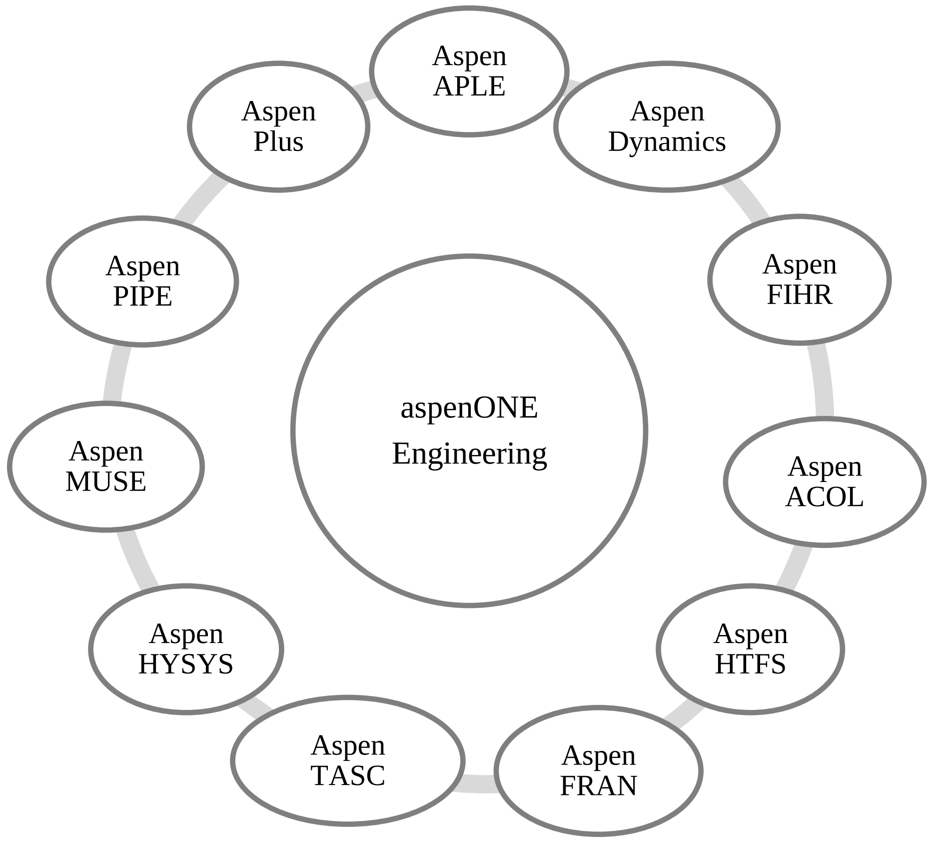


Fig: 3.2 aspenONE engineering classification

3.3 Introduction to Aspen Hysys

The simulations of the Nitrogen liquefaction cycle have been carried out using Aspen Hysys, which is chemical process simulation modeling software.

The flow sheet (PFD) includes a library of standard unit operation blocks and logical units (e.g. cooler, mixer, Heat-exchangers, separator, splitters, compressor, Recycle, spreadsheet, set, adjust), which represent processes taking place in an actual liquefaction plant. HYSYS is a combination of tools that are used for estimating the physical properties and liquid-vapour phase

Equilibrium of various inbuilt components. These components are the substances that are used within the plant for the feeds, within the reaction and separation sections. The program is such that it will converge energy and material balances and has standard unit operations typical of any processing plant. HYSYS updates the calculations as the user enters information and does as much as it can at that time. The successful completion of an operation is seen by the changes in colour on screen. HYSYS is not just a steady state program. A case can be transferred into a dynamic simulation where process controllers can be added, and hence, realistically evaluate a plant wide control philosophy

For the Liquefaction process to be modelled in HYSYS, there must be a foundation on which the components must be modeled. In this process, there are one components involved in the chemistry that is nitrogen. Nitrogen is selected as pure components within the simulation basis manager. The next task is to assign a fluids package, which is used by the software to calculate the component streams as they change within the HYSYS flow sheet. The selection of the fluids package is critical. There are dangers of using an incorrect thermodynamics package. They state, "Everything from the energy balance to the volumetric flow rates to the separation in the equilibrium-stage units depends on accurate thermodynamic data". For simulation of nitrogen liquefaction cycle, BWRS equation of state is used in this project work.

3.4 Equation of state

In physics and thermodynamics, an equation of state is a relation between state variables. More specifically, an equation of state is a thermodynamic equation describing the state of matter under a given set of physical conditions. It is a constitutive equation which provides a mathematical relationship between two or more state functions associated with the matter, such as its temperature, pressure, volume, or internal energy. Equations of state are useful in describing the properties of fluids, mixtures of fluids, solids, and even the interior of stars.

Aspen HYSYS contain various property packages, but for simulation of Nitrogen liquefication cycle BWRS equation of state is used and for helium liquefication cycle peng-Robinson equation of state is used because it doesn't allow for helium gas.

3.4.1 Peng-Robinson:

Peng-Robinson is a Cubic equation of state

$$P = \frac{RT}{V_m - b} - \frac{a\alpha}{V_m^2 + 2bV_m - b^2}$$

$$a = \frac{0.45724 R^2 T_c^2}{p_c}$$

$$b = \frac{0.07780 R T_c}{p_c}$$

$$\alpha = (1+(0.37464+1.54226\omega - 0.26992\ \omega^2)\ (1-T_r^{0.5}))^2$$

$$Tr = \frac{T}{T_c}$$

In polynomial form:

$$A = \frac{a\alpha p}{R^2 T^2}$$

$$B = \frac{bp}{RT}$$

$$Z^3 - (1\text{-}B)\, Z^2 + (A\text{-}3B^2\text{-}2B)\, Z - (AB\text{-}B^2\text{-}B^3) = 0$$

where, ω is the acentric factor of the species and *R* is the universal gas constant.

The Peng-Robinson equation was developed in 1976 in order to satisfy the following goals:

1. The parameters should be expressible in terms of the critical properties and the acentric factor.
2. The model should provide reasonable accuracy near the critical point, particularly for calculations of the compressibility factor and liquid density.
3. The mixing rules should not employ more than a single binary interaction parameter, which should be independent of temperature pressure and composition.
4. The equation should be applicable to all calculations of all fluid properties in natural gas processes.

For the most part the Peng-Robinson equation exhibits performance similar to the Soave equation, although it is generally superior in predicting the liquid densities of many materials, especially nonpolar ones. The departure functions of the Peng-Robinson equation are given on a separate article.

3.4.2 BWRS (Benedict-Webb-Rubin):

BWRS is an non-cubic equation

$$P = \rho RT + \left(B_0RT - A_0 - \frac{C_o}{T^2} + \frac{D_o}{T^3} - \frac{E_o}{T^4}\right)\rho^2 + \left(bRT - a - \frac{d}{T}\right)\rho^3 + \left(a + \frac{d}{T}\right)\rho^6 + \frac{c\rho^3}{T^2}\left(1+\gamma\rho^2\right)\exp(-\gamma\rho^2)$$

3.5 Simulation Environment

The Simulation environment contains the main flow sheet where you do the majority of your work (installing and defining streams, unit operations, columns and sub flow sheets). Before entering the Simulation environment, you must have a fluid package with selected components in the component list and a property package.

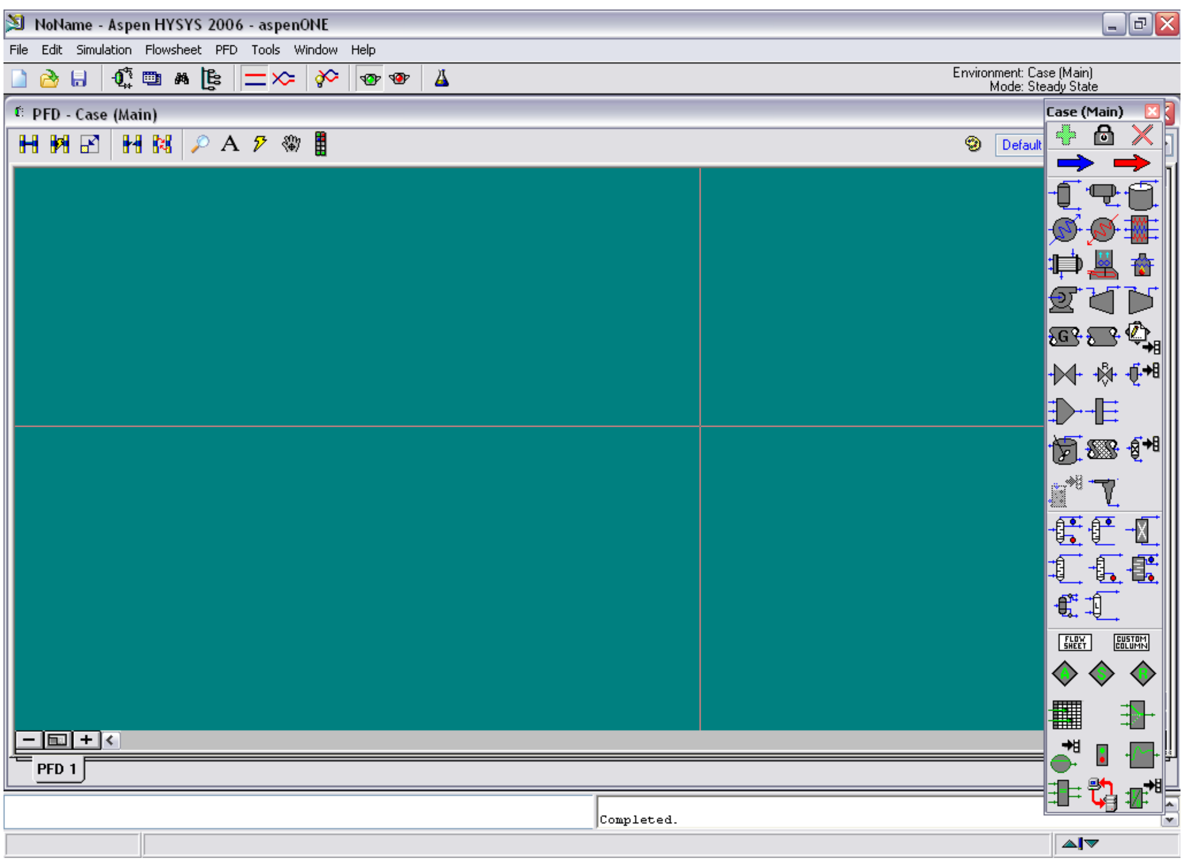


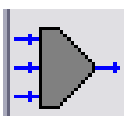
Fig: 3.3 simulation environment

The flow sheet in Aspen HYSYS shows the various components and the material streams needed to bring about the liquefaction of the nitrogen gas. It consists of various apparatus(Object Palette) but few object which are in our use are as mixer, an isentropic compressor, a chiller, a LNG countercurrent heat exchanger, an isenthalpic J-T valve, a separator which performs flash separation operations and logical operation units Set, Spreadsheet and Recycle.

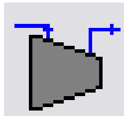
3.6 The components or the blocks or the equipments

The description of the various components and the conditions at which they operate are described subsequently.

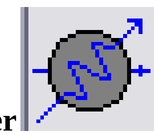
3.6.1 HYSYS object

A. Mixer 

The Mixer operation combines two or more inlet streams to produce a single outlet stream. A complete heat and material balance is performed with the Mixer. That is, the one unknown temperature among the inlet and outlet streams is always calculated rigorously. If the properties of all the inlet streams to the Mixer are known (temperature, pressure, and composition), the properties of the outlet stream is calculated automatically since the composition, pressure, and enthalpy is known for that stream.

B. Compressor 

There are various type of compressor that are available in market but in Aspen Hysys option of isentropic centrifugal compressor is available. The Centrifugal Compressor operation is used to increase the pressure of an inlet gas stream with relative high capacities and low compression ratios. Depending on the information specified, the Centrifugal Compressor calculates either a stream property (pressure or temperature) or a compression efficiency.

C. Cooler/Chiller 

The Cooler operations are one-sided heat exchangers. The inlet stream is cooled (or heated) to the required outlet conditions, and the energy stream absorbs (or provides) the enthalpy difference between the two streams. These operations are useful when you are interested only in how much energy is required to cool or heat a process stream with a utility, but you are not interested in the conditions of the utility itself.

D. Heat Exchanger / LNG

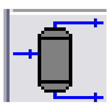
The LNG (Liquefied Natural Gas) exchanger model solves heat and material balances for multi-stream heat exchangers and heat exchanger networks. The solution method can handle a wide variety of specified and unknown variables. For the overall exchanger, you can specify various parameters, including heat leak/heat loss, UA or temperature approaches. Two solution approaches are employed; in the case of a single unknown, the solution is calculated directly from an energy balance. In the case of multiple unknowns, an iterative approach is used that attempts to determine the solution that satisfies not only the energy balance, but also any constraints, such as temperature approach or UA.

Heat Transfer Theory of LNG

The LNG calculations are based on energy balances for the hot and cold fluids. The following general relation applies any layer in the LNG unit operation.

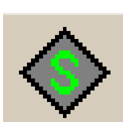
where:

$$m\,(h_{in} - h_{out}) + Q_{internal} + Q_{external} = \rho \frac{d(vh_{out})}{dt}$$

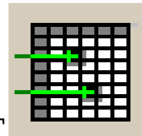
E. Separator 

Multiple feeds, one vapour and one liquid product stream. In Steady State mode, the Separator divides the vessel contents into its constituent vapour and liquid phases

3.6.2 Logical Units

A. SET 

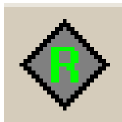
SET is used to set the value of a specific process variable (PV in the manuals) in relation to another PV. The relation must be of the form Y = mX + b and the process variables must be of the same type. For example, you could use the SET to set one material streams temperature to always be 20 degrees hotter than another material stream's temperature. SET may work both ways (i.e. if the target is known and not the source, the target will "set" the source).

B. SPREADSHEET 

The Spreadsheet applies the functionality of Spreadsheet programs to flowsheet modeling. With essentially complete access to all process variables, the Spreadsheet is extremely powerful and has many applications in HYSYS. The HYSYS Spreadsheet has standard row/column functionality. You can import a variable, or enter a number or formula anywhere in the spreadsheet.

The Spreadsheet can be used to manipulate or perform custom calculations on flowsheet variables. Because it is an operation calculations are performed automatically; Spreadsheet cells are updated when flowsheet variables change.

One application of the Spreadsheet is the calculation of pressure drop during dynamic operation of a Heat Exchanger. In the HYSYS Heat Exchanger, the pressure drop remains constant on both sides regardless of flow. However, using the Spreadsheet, the actual pressure drop on one or both sides of the exchanger could be calculated as a function of flow. Complex mathematical formulas can be created, using syntax which is similar to conventional Spreadsheets. Arithmetic, logarithmic, and trigonometric functions are examples of the mathematical functionality available in the Spreadsheet. The Spreadsheet also provides logical programming in addition to its comprehensive mathematical capabilities

C. RECYCLE 

Use this operation every time you need to recycle a stream. The logical block connects the two streams around the tear (remember the tear does not have to be the official "recycle" stream itself, but instead should be the best place in the loop to make the break for convergence purposes). Before you can install the RECYCLE the flow sheet must have completed. That means there need to be values for both the assumed stream and the calculated stream. Once the Recycle is attached and running, HYSYS compares the two values, adjusts the assumed stream, and runs the flow sheet again. HYSYS repeats this process until the two streams match within specified tolerances.

Those tolerances are set on the Parameters Page. There are tolerances for Vapour Fraction, Temperature, Pressure, Flow, Enthalpy, and Composition. The tolerances you enter are *not* absolute. They are actually multipliers for HYSYS' internal convergence tolerances. For example, the internal value for Temperature is .01 degrees (note that is in Kelvin, because HYSYS does all of its calculations in an internal unit set), so a multiplier often means the two streams must be within a tenth of a degree of each other.

On the Numerical Page, among other things, you may set the RECYCLE to either Nested (the Op is called whenever it is encountered in the flow sheet) or Simultaneous (all of the RECYCLEs are invoked)

Chapter: 4

RESULT

4.1 Simulation of Linde cycle

<u>Problem specification:</u> 1

To solve Linde cycle, (using ASPEN-HYSYS) as simulation tool.

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1 bar,

P_{max} = 100 bar, 150bar, 200bar, 250bar, 300bar, 350bar, 400bar, 450bar, 500bar, 550bar, 600bar

Minimum temperature approach in HX= 10K,

Pressure drop (except valve) is zero

Fluid package = BWRS

Fluid = pure nitrogen

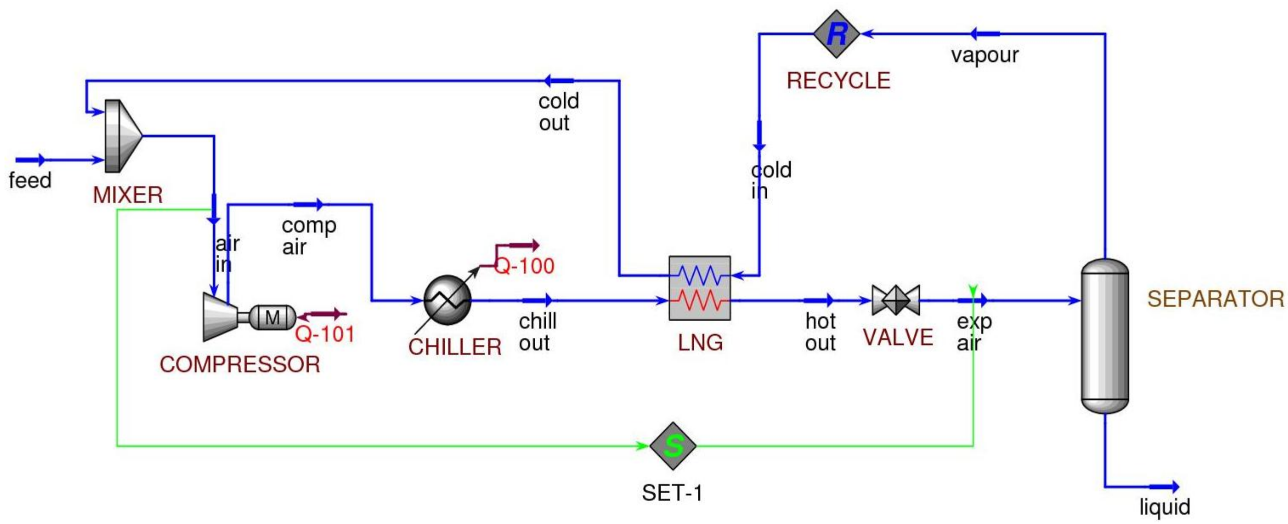


Fig: 4.1 PFD of Linde cycle

Pressure	100	150	200	250	300	350
Yield	1.89E-02	3.40E-02	4.22E-02	5.18E-02	5.65E-02	5.89E-02

Pressure	400	450	500	550	600
Yield	5.97E-02	5.91E-02	5.75E-02	5.48E-02	5.14E-02

Table: 4.1 variation of yield with pressure

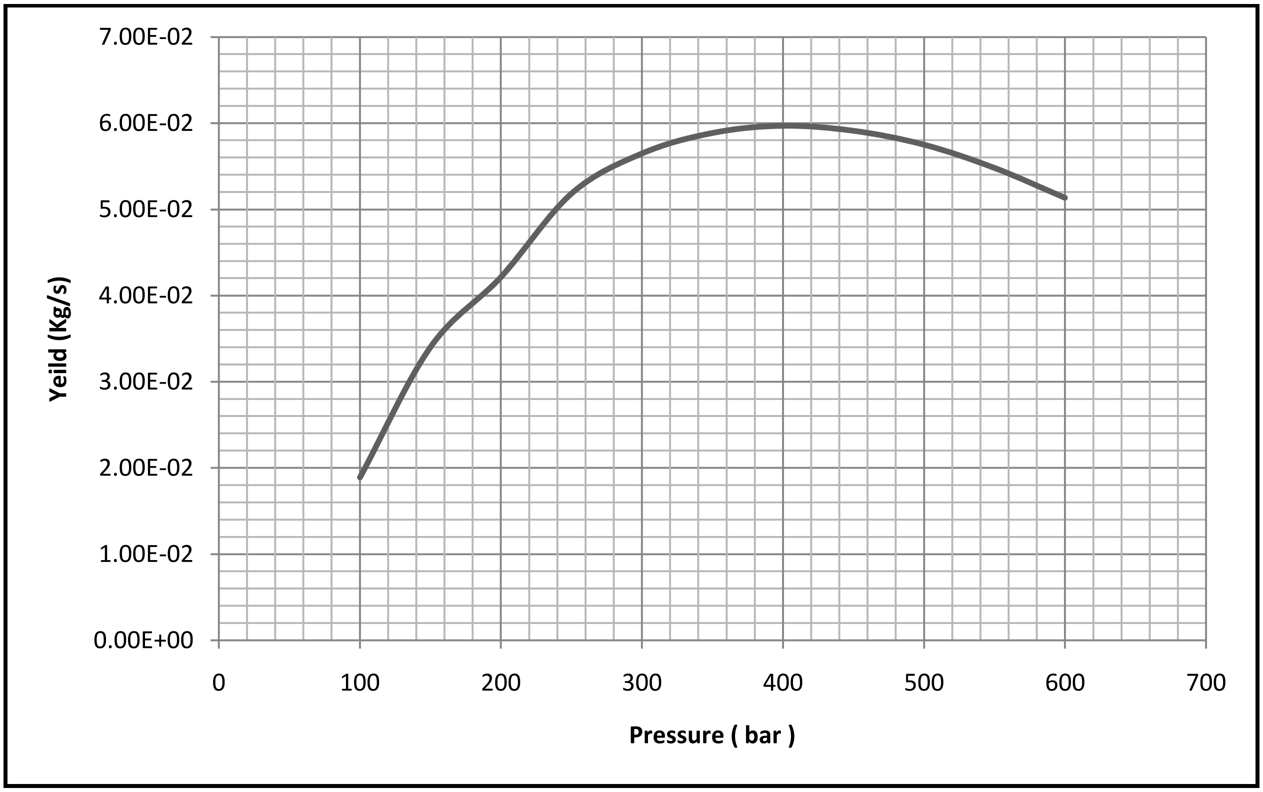


Fig: 4.2 Yield vs pressure plot for linde system

<u>Problem specification:</u> 2

To solve Linde cycle, (using ASPEN-HYSYS) as simulation tool.

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1 bar,

P_{max} = 200bar

Minimum temperature approach in HX= 0 K to 50K,

Pressure drop (except valve) is zero

Fluid package = BWRS

Fluid = pure nitrogen

Min approach (k)	0	3	5	10	15	20	25	29
Yeild (%)	6.68E-02	6.02E-02	5.59E-02	4.47E-02	3.31E-02	2.12E-02	9.26E-03	0.00

Table: 4.2 variation of yield with minimum approach of heat exchanger

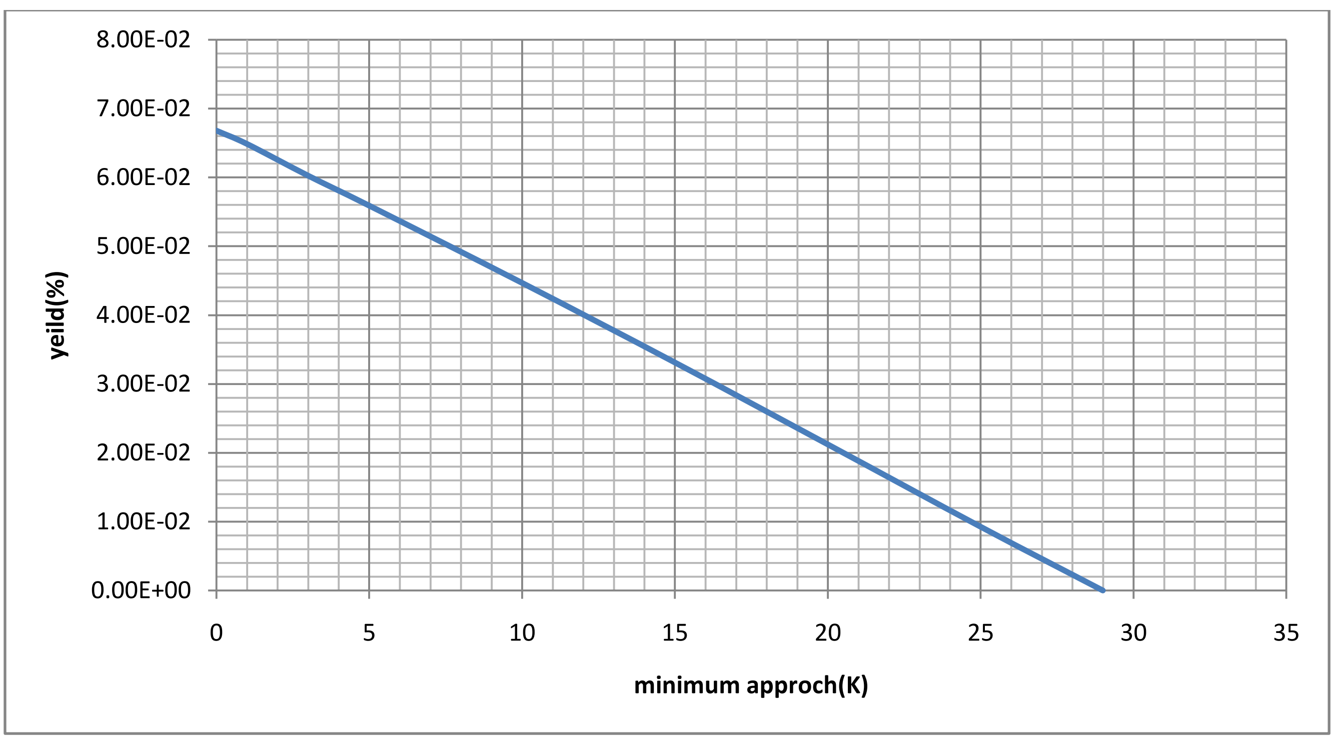


Fig: 4.3 variation of yield with minimum approach of heat exchanger

4.1.1 Figure of merit:

FOM for linde cycle is given as :

$$\text{FOM} = \left(\frac{T_1\left(s_1-s_f\right)-(h_1-h_f)}{T_1(s_1-s_2)-(h_1-h_2)}\right)*\left(\frac{h_1-h_f}{h_1-h_2}\right)$$

Case- 1: FOM for minimum approach of 0 K

$$\text{FOM} = \left(\frac{300(186.8-69.28)-(47.67-(-1.246E4))}{300(186.8-139.7)-(47.67-(789.4))}\right)*\left(\frac{47.67-(-789.4))}{47.67-(-1.246E4))}\right)$$

$$= \left(\frac{35256-12507.67}{14130-837.07}\right)*\left(\frac{837.07}{12507.67}\right)$$

$$= \left(\frac{322748.33}{13292.93}\right)*\left(\frac{837.07}{12507.67}\right)$$

$$= 0.11$$

Case- 2: FOM for minimum approach of 10 K

$$\text{FOM} = \left(\frac{290.4(185.8-69.28)-(-231-(-1.246E4))}{290.4(185.8-139.7)-(-231-(789.4))}\right)*\left(\frac{-231-(-789.4))}{-231-(-1.246E4))}\right)$$

$$= \left(\frac{21605.504}{12829.04}\right)*\left(\frac{558.4}{12229}\right)$$

$$= 0.07689$$

4.2 Simulation of Claude cycle

<u>Problem specification</u>: 3

To solve Claude cycle, (using ASPEN-HYSYS) as simulation tool to find the value of x the minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1.1 bar,

P_{max} = 8 bar,

Minimum temperature approach in HX_1= 3K, HX_2= 2K, HX_3= 1K

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 40 %

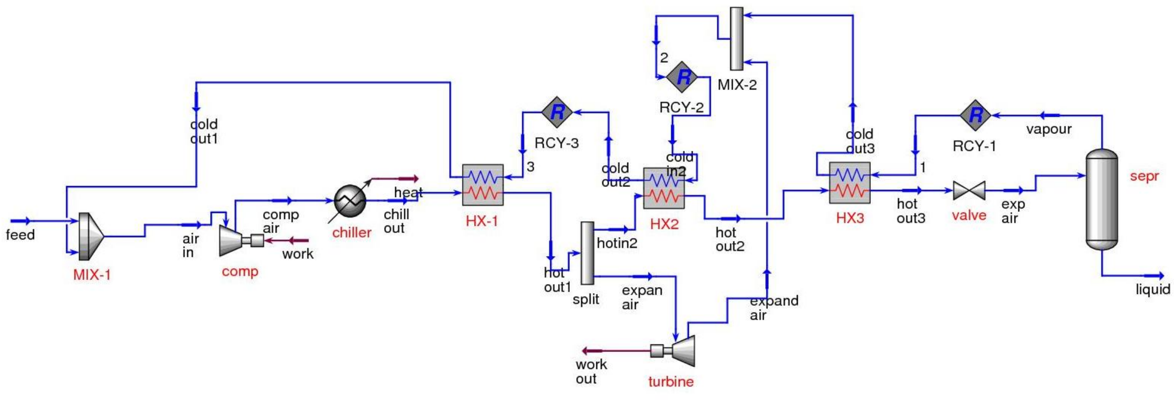
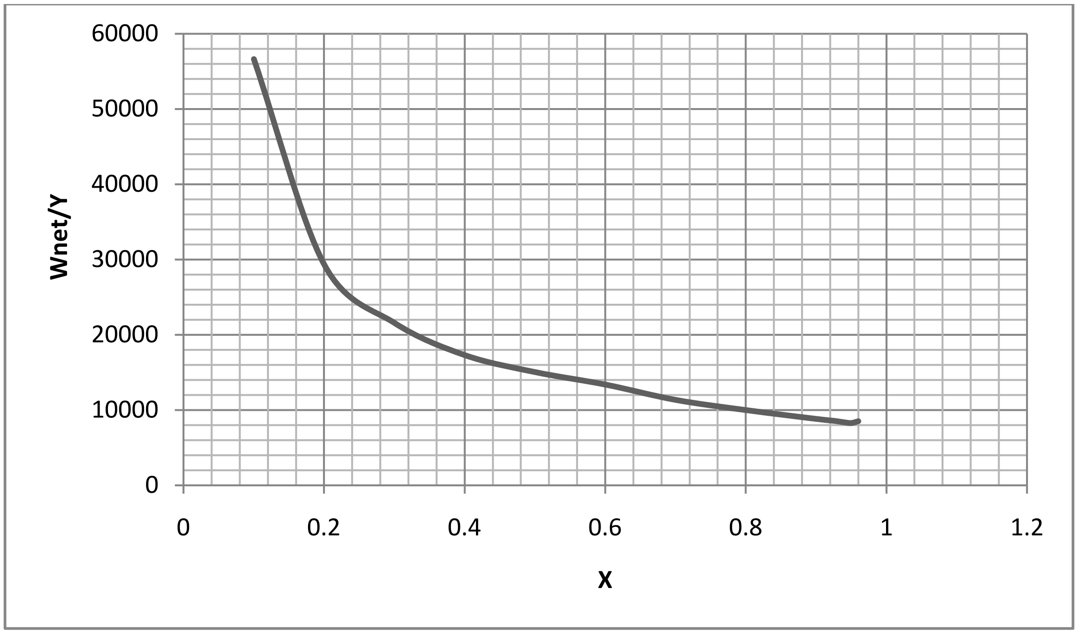


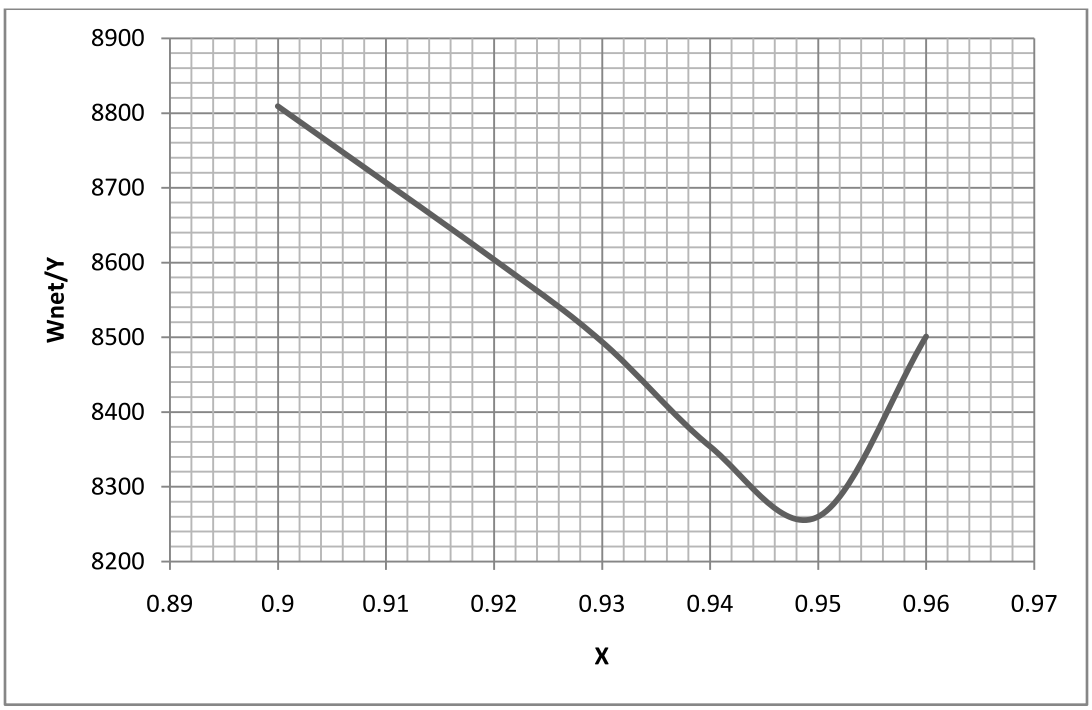
Fig: 4.4 Claude PFD

W_{comp} (KW)	$W_{chiller}$ (KW)	$W_{turbine}$ (KW)	χ	W_{net} (KW)	Y	W_{net} /Y
313	311.4	3.849	0.1	309.151	5.46E-03	56613
313	311.4	6.065	0.2	306.935	1.05E-02	29331
313	311.4	7.842	0.3	305.158	1.42E-02	21561
313	311.4	9.167	0.4	303.833	1.76E-02	17284
313	311.5	10.25	0.5	302.75	2.01E-02	15029
313	311.5	11.33	0.6	301.67	2.26E-02	13371
313	311.5	12.94	0.7	300.06	2.65E-02	11334
313	311.5	14.58	0.8	298.42	2.99E-02	9979
313	311.5	16.2	0.9	296.8	3.37E-02	8809
313	311.6	16.53	0.92	296.47	3.45E-02	8604
313	311.6	16.69	0.93	296.31	3.49E-02	8494
313	311.6	16.85	0.94	296.15	3.54E-02	8354
313.1	311.6	17.02	0.95	296.08	3.58E-02	8260
313	311.6	16.61	0.96	296.39	3.49E-02	8501

Table: 4.3 Net works required to liquefy nitrogen at different value of x without effectiveness



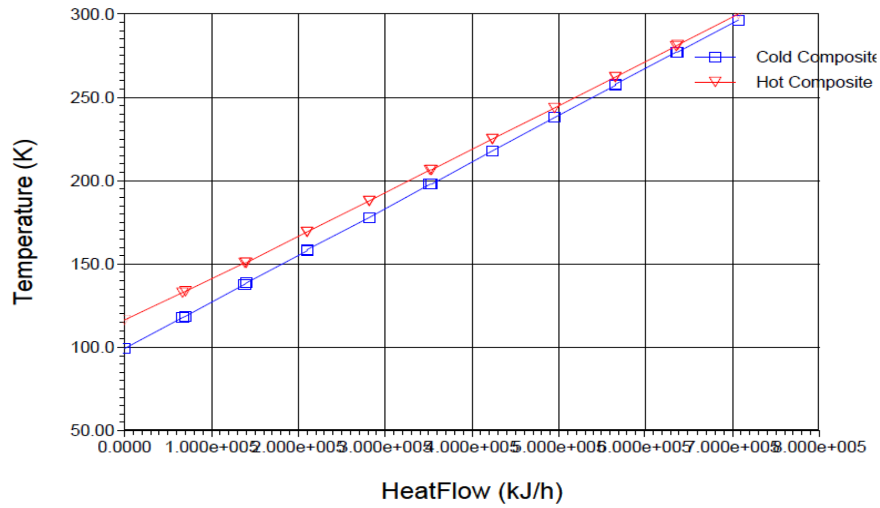
(a)



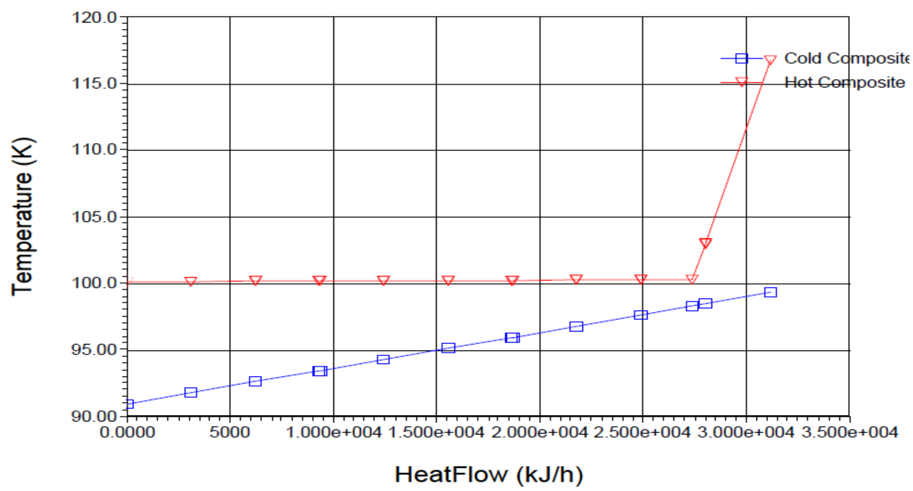
(b)

Fig: 4.5 Work required liquefying a unit mass of nitrogen in the Claude system

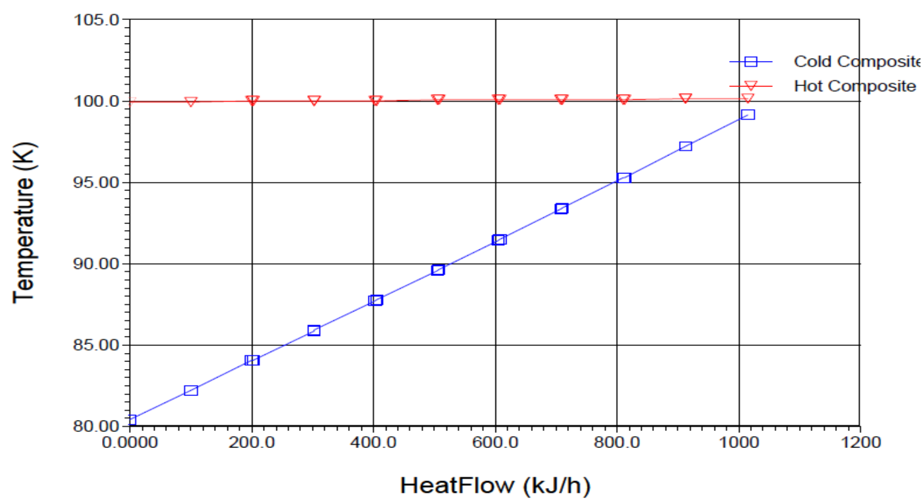
(a) Full plot , (b) magnify plot



(a)



(b)



(c)

Fig: 4.6 Temperature profile in heat exchanger at optimum value

(a) First HX (b) second HX (c) third HX

<u>Problem specification</u>:4

To solve Claude cycle, (using ASPEN-HYSYS) as simulation tool to find the value of x where minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1.1 bar,

P_{max} = 8 bar,

Minimum temperature approach in, HX_2= 2K, HX_3= 1K

Effectiveness in heat exchanger1 = 0.99

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 40 %

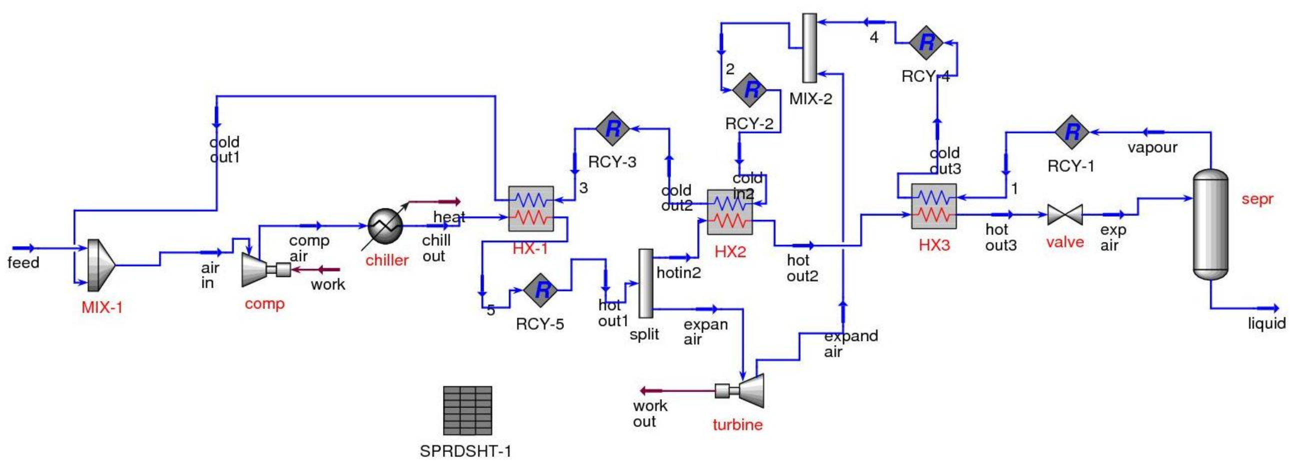
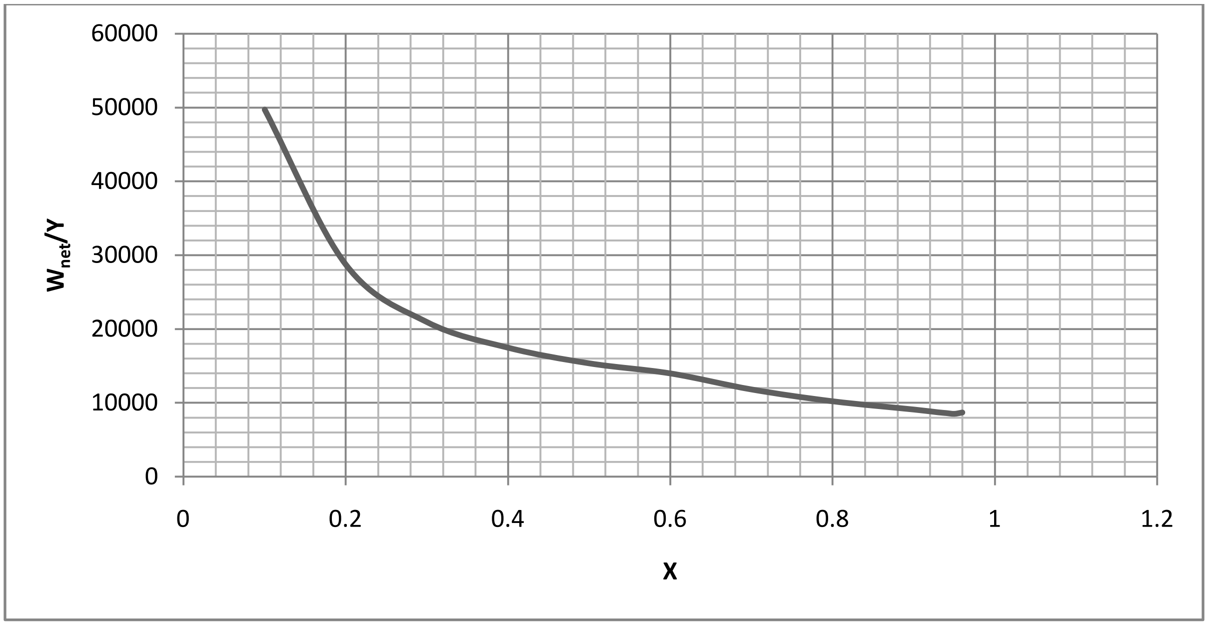


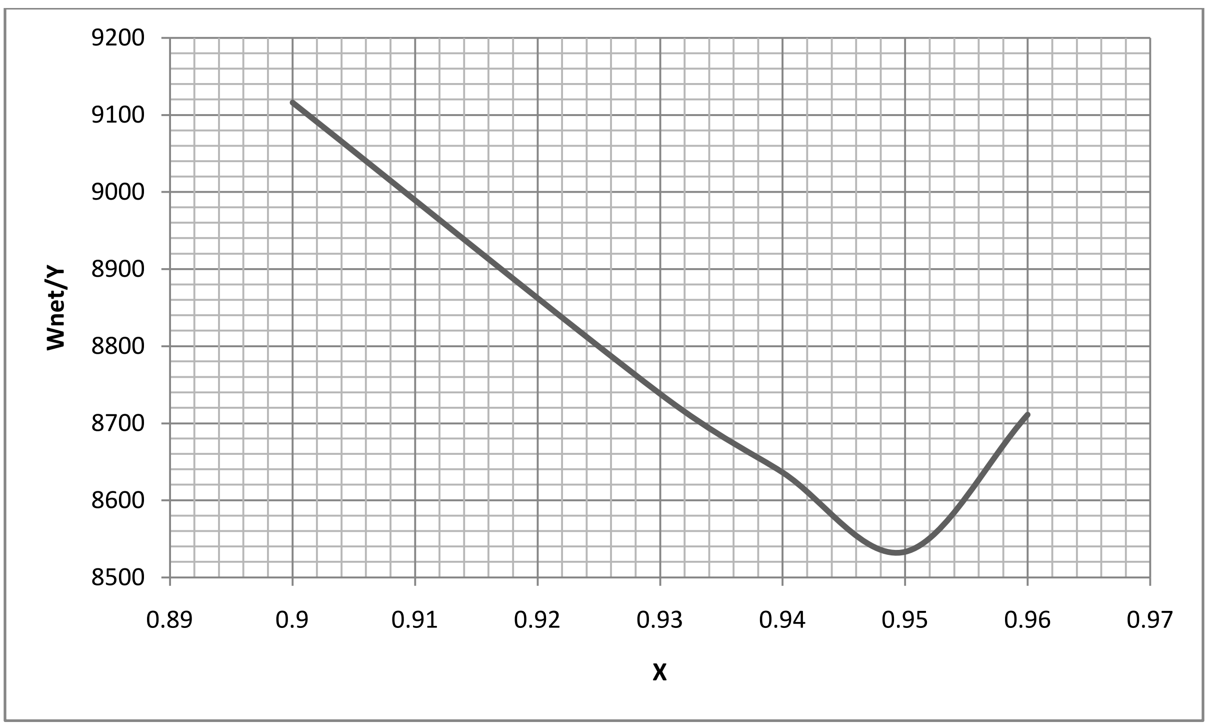
Fig: 4.7 Claude PFD with effectiveness in first HX

W_{comp} (KW)	$W_{chiller}$ (KW)	$W_{turbine}$ (KW)	χ	W_{net} (KW)	Y	W_{net} /Y
313.7	312.9	3.608	0.1	310.092	6.24E-03	49730
313.3	312.1	5.934	0.2	307.366	1.07E-02	28739
313.1	311.6	7.679	0.3	305.421	1.46E-02	20958
312.9	311.9	9.094	0.4	303.806	1.74E-02	17488
312.8	311	10.21	0.5	302.59	1.97E-02	15370
312.7	310.8	11.26	0.6	301.44	2.15E-02	14007
312.6	310.7	12.86	0.7	299.74	2.53E-02	11836
312.6	310.7	14.47	0.8	298.13	2.91E-02	10233
312.6	310.7	16.1	0.9	296.5	3.25E-02	9116
312.6	310.7	16.58	0.93	296.02	3.39E-02	8738
312.6	310.7	16.74	0.94	295.86	3.43E-02	8636
312.6	310.7	16.9	0.95	295.7	3.47E-02	8533
312.6	310.6	16.77	0.96	295.83	3.40E-02	8711

Table: 4.4 Net works required to liquefy nitrogen at different value of x with effectiveness



(a)



(b)

Fig: 4.8 Optimum work required liquefying a unit mass of nitrogen in the Claude system

(a) Full plot , (b) magnify plot

Stream	Heat Exchanger 1		Heat Exchanger 2		Heat Exchanger 3		χ
	Inlet Temp	Outlet Temp	Inlet Temp	Outlet Temp	Inlet Temp	Outlet Temp	
Hot	300	234.9873817	234.98738	205.9133847	205.9134	99.98329836	0.1
Cold	230.74357	297.0000374	203.91339	230.7448434	80.47354	204.9133785	
Hot	300	187.3291029	187.3291	160.0016677	160.0017	99.98144135	0.2
Cold	180.955608	297.0000094	158.0017	180.9626182	80.4751	159.001674	
Hot	300	162.5113138	162.51131	136.6633889	136.6634	99.97988856	0.3
Cold	154.184043	297.0000084	134.66339	154.1590752	80.47787	135.6633934	
Hot	300	145.4887875	145.48879	120.9300694	120.9301	99.98121968	0.4
Cold	135.290818	297.0000094	118.93013	135.2908181	80.47548	119.9300976	
Hot	300	132.4287429	132.42874	108.6749137	108.6749	99.98286489	0.5
Cold	120.376241	297.0000092	106.67491	120.3839175	80.47557	107.6749112	
Hot	300	123.045602	123.0456	100.1715691	100.1699	99.98172878	0.6
Cold	109.237594	297.000013	97.817001	109.2201367	80.47701	99.16990122	
Hot	300	120.6106759	120.55241	100.1692879	100.1724	99.98317238	0.7
Cold	105.634559	296.9999948	95.859474	105.6462591	80.47463	99.17244586	
Hot	300	118.7951288	118.86473	100.1713003	100.1703	99.9814977	0.8
Cold	102.833055	296.9999937	94.013849	102.8272339	80.47565	99.17025042	
Hot	300	117.397003	117.4815	100.1684378	100.1681	99.98197968	0.9
Cold	100.41723	296.9999835	92.086632	100.4349266	80.47534	99.16810968	
Hot	300	117.1572037	117.24192	100.1721626	100.1709	99.9823053	0.92
Cold	99.9907895	297.0000659	91.701077	99.99891265	80.47624	99.17094508	
Hot	300	117.0580251	117.1267	100.1683684	100.1691	99.98173797	0.93
Cold	99.7919159	297.0001304	91.510632	99.78421232	80.47505	99.1691329	
Hot	300	116.9583199	116.95832	100.17144	100.1694	99.98222408	0.94
Cold	99.5655898	297	91.260588	99.56968262	80.47504	99.16941655	
Hot	300	116.8946362	116.89464	100.1717553	100.1699	99.98159411	0.95
Cold	99.3743943	297.000008	91.061583	99.36409725	80.47577	99.16983826	
Hot	300	112.7289117	112.72891	88.84143951	88.84144	88.44846541	0.96
Cold	94.5922938	297.0000087	86.841458	94.59229383	80.47536	87.84143917	

Table: 4.5 Temperature across heat exchanger at different value of x

For low pressure Claude system we can see from above table it can be seen that at optimum valve (0.95) temperature drop in hot stream of cold heat exchanger is 0.39297K (negligible) and temperature increase in cold stream is 18.694K. So third heat exchanger or low temperature heat exchanger of Claude system if neglected it not cause any appreciable difference in output of Claude system at optimum operating condition. This modified Claude system with two (first and second) heat exchanger system is known as kapitza system.

4.3 Simulation of Kapitza cycle

<u>Problem specification:</u> 5

To solve kapitza system, (using ASPEN-HYSYS) as simulation tool to find the value of x where minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1.1 bar,

P_{max} = 8 bar,

Minimum temperature approach in HX_1= 3K, HX_2= 2K,

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 40 %

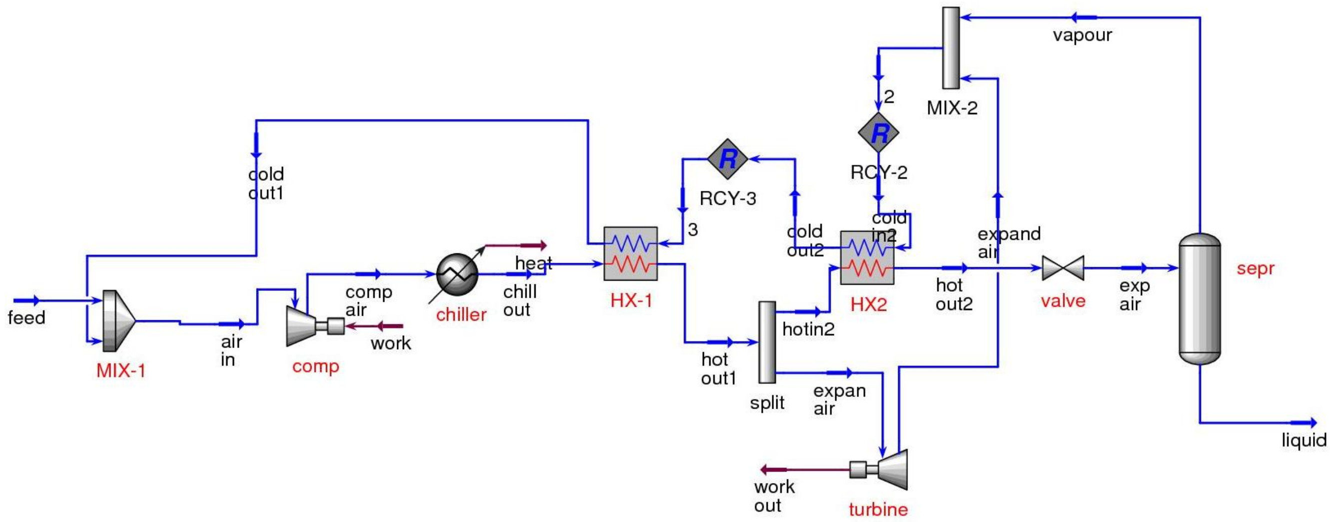
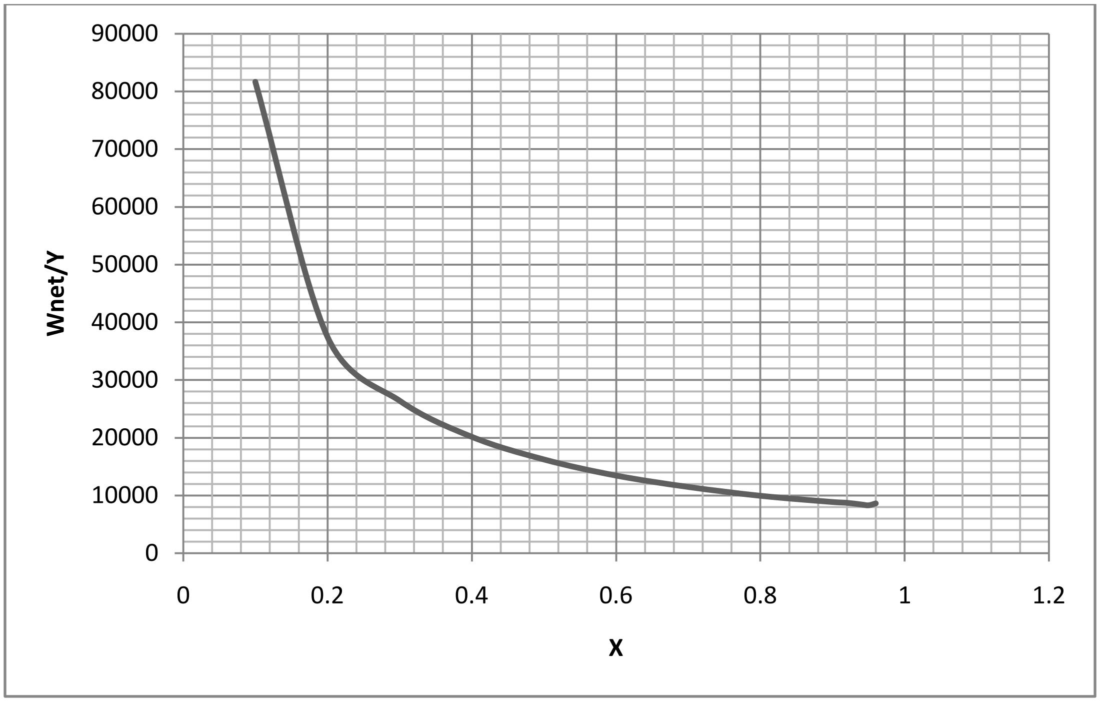


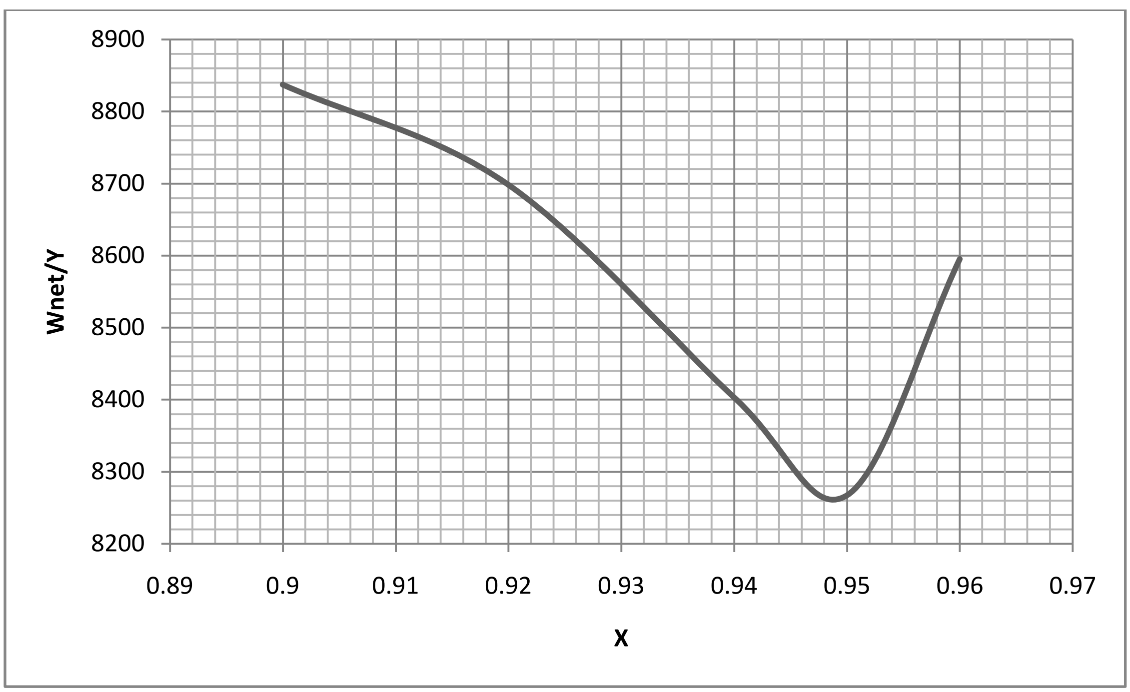
Fig: 4.9 Kapitza PFD

W_{comp} (KW)	$W_{chiller}$ (KW)	$W_{turbine}$ (KW)	χ	W_{net} (KW)	Y	W_{net} /Y
313	311.4	3.245	0.1	309.755	3.79E-03	81671
313	311.4	5.119	0.2	307.881	8.22E-03	37463
313	311.4	6.669	0.3	306.331	1.16E-02	26393
313	311.4	8.195	0.4	304.805	1.51E-02	20137
313	311.5	9.763	0.5	303.237	1.87E-02	16215
313	311.5	11.35	0.6	301.65	2.25E-02	13419
313	311.5	12.95	0.7	300.05	2.62E-02	11449
313	311.5	14.56	0.8	298.44	3.01E-02	9916
313	311.5	16.2	0.9	296.8	3.36E-02	8837
313	311.6	16.53	0.92	296.47	3.41E-02	8698
313	311.6	16.4	0.94	296.6	3.53E-02	8403
313	311.6	17	0.95	296	3.58E-02	8267
313	311.6	16.54	0.96	296.46	3.45E-02	8595

Table: 4.6 Net works required to liquefy nitrogen at different value of x for kapitza system



(a)



(b)

Fig: 4.10 Optimum work required liquefying a unit mass of nitrogen in the Kapitza system

(a) Full plot , (b) magnify plot

If we compare Claude Table 4.2 and kapitza Table 4.5 we can see that at initial or when mass flow through turbine is less work required to liquefy unit mass of nitrogen is more in kapitza system (two heat exchange system) as compare to Claude system (three heat exchanger) while it can be observed that at optimum value work required to liquefy unit mass is almost same as of Claude system as well as optimum value is also same. It can be seen in overlap plot for kapitza and Claude net work require to liquefy nitrogen

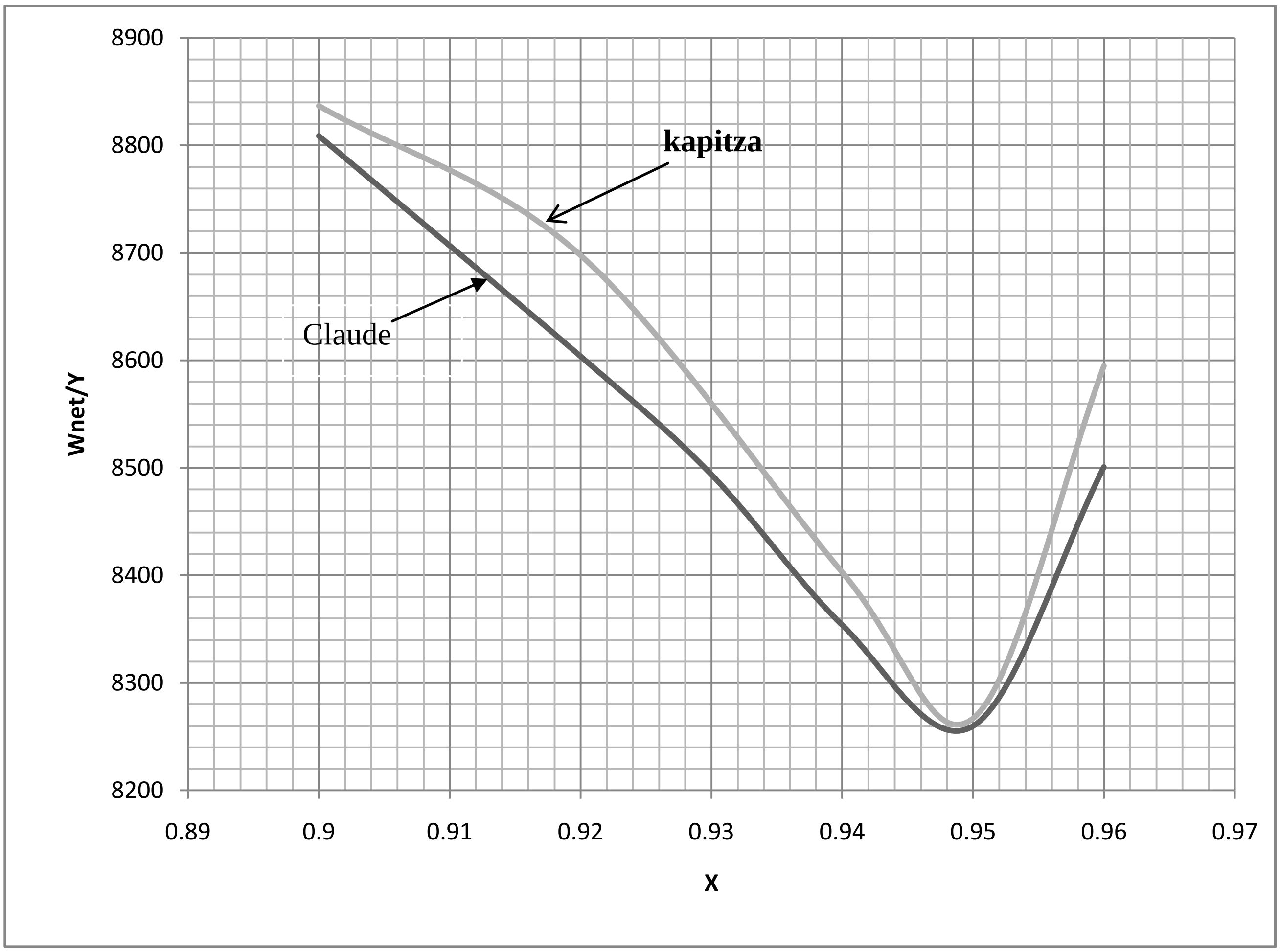


Fig: 4.11 comparison of work required to liquefy unit mass of nitrogen

4.4 Simulation of Claude cycle for Haylent

Problem specification: 6

To solve Claude system, (using ASPEN-HYSYS) as simulation tool to find the value of x where minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1.1 bar,

P_{max} = 150 bar,

Minimum temperature approach in HX_1= 3K, HX_2= 2K, HX_3= 1K

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 70 %

W_{comp} (KW)	$W_{chiller}$ (KW)	$W_{turbine}$ (KW)	χ	W_{net} (KW)	Y	W_{net} /Y
1247	1270	29.71	0.2	1217.29	0.122327	9951
1247	1270	44.56	0.3	1202.44	0.156666	7675
1248	1270	58.41	0.4	1189.59	0.18643	6380
1248	1271	69.39	0.5	1178.61	0.212245	5553
1248	1271	78.16	0.6	1169.84	0.23242	5033
1248	1271	78.89	0.61	1169.11	0.234236	4991
1248	1271	79.52	0.62	1168.48	0.232441	5027

Table: 4.7 Net works required to liquefy nitrogen at different value of x for Claude system

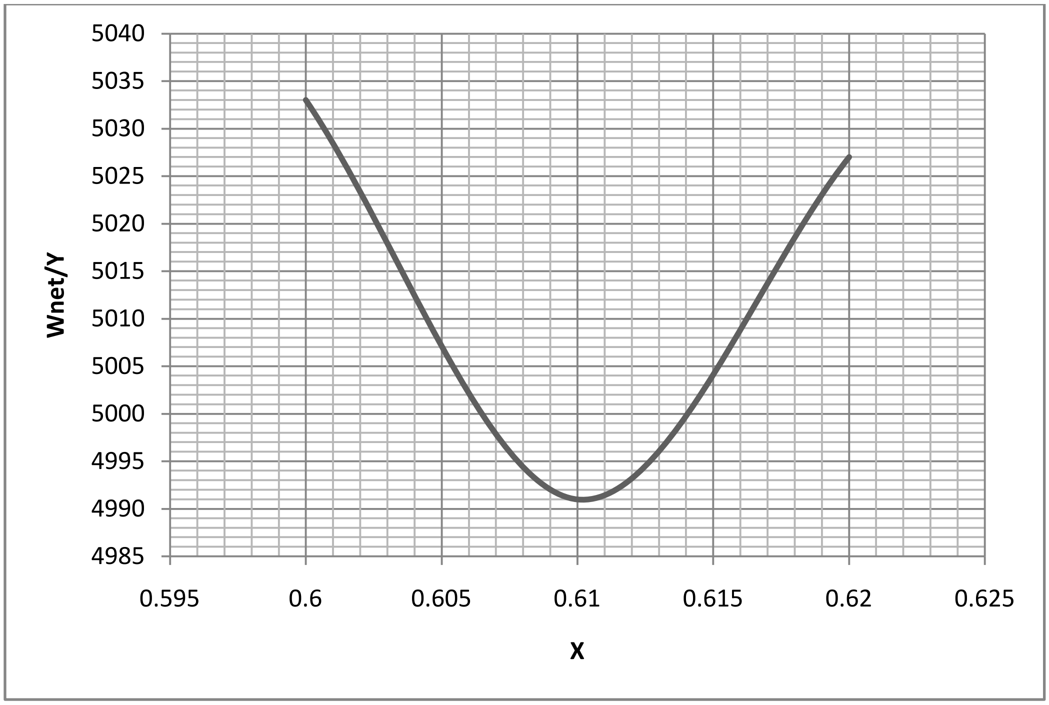


Fig: 4.12 Optimum work required liquefying a unit mass of nitrogen in the claude system

4.5 Simulation of Haylent system

Problem specification: 7

To solve Claude system, (using ASPEN-HYSYS) as simulation tool to find the value of x where minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 300K, $P_{ambient}$ = 1.1 bar,

P_{max} = 150 bar,

Minimum temperature approach in HX_2= 2K, HX_3= 1K

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 70 %

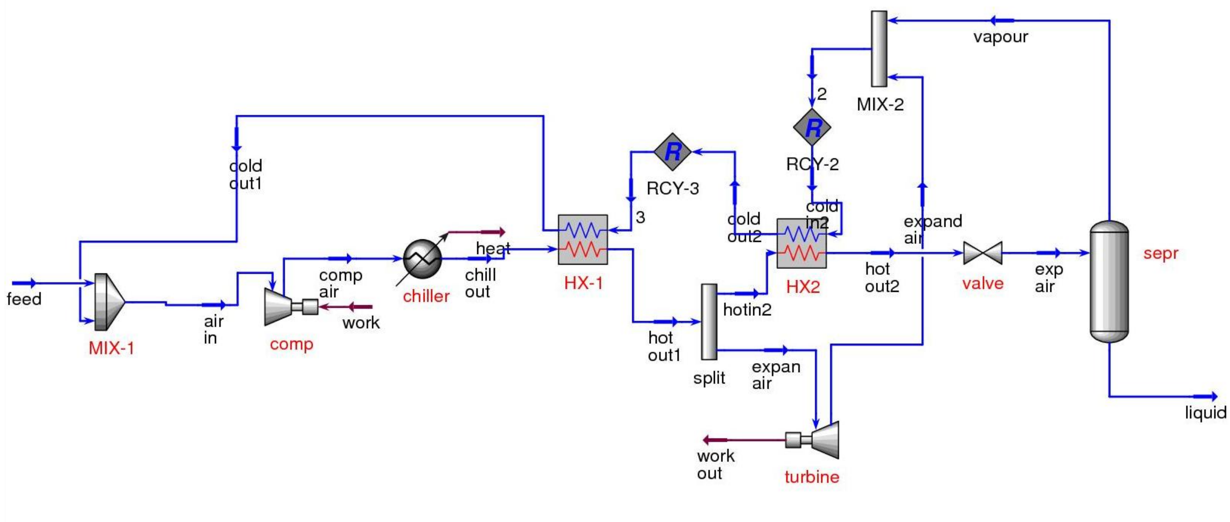


Fig: 4.13 Haylent PFD

W_{comp} (KW)	$W_{chiller}$ (KW)	$W_{turbine}$ (KW)	χ	W_{net} (KW)	Y	W_{net} /Y
1212	1235	29.72	0.2	1182.28	0.122264	9669
1212	1236	44.58	0.3	1167.42	0.156643	7452
1202	1222	59.4	0.4	1142.6	0.184114	6205
1170	1182	74.3	0.5	1095.7	0.198412	5522
1147	1152	81.73	0.55	1065.27	0.200576	5311
1116	1113	89.16	0.6	1026.84	0.198115	5183
1101	1093	92.13	0.62	1008.87	0.195474	5161
1092	1083	93.62	0.63	998.38	0.193757	5152
1081	10.68	95.1	0.64	985.9	0.190023	5188
1067	1051	96.59	0.65	970.41	0.184731	5253
997.3	962	104	0.7	893.3	0.158495	5636

Table: 4.8 Net works required to liquefy nitrogen at different value of x for Haylent system

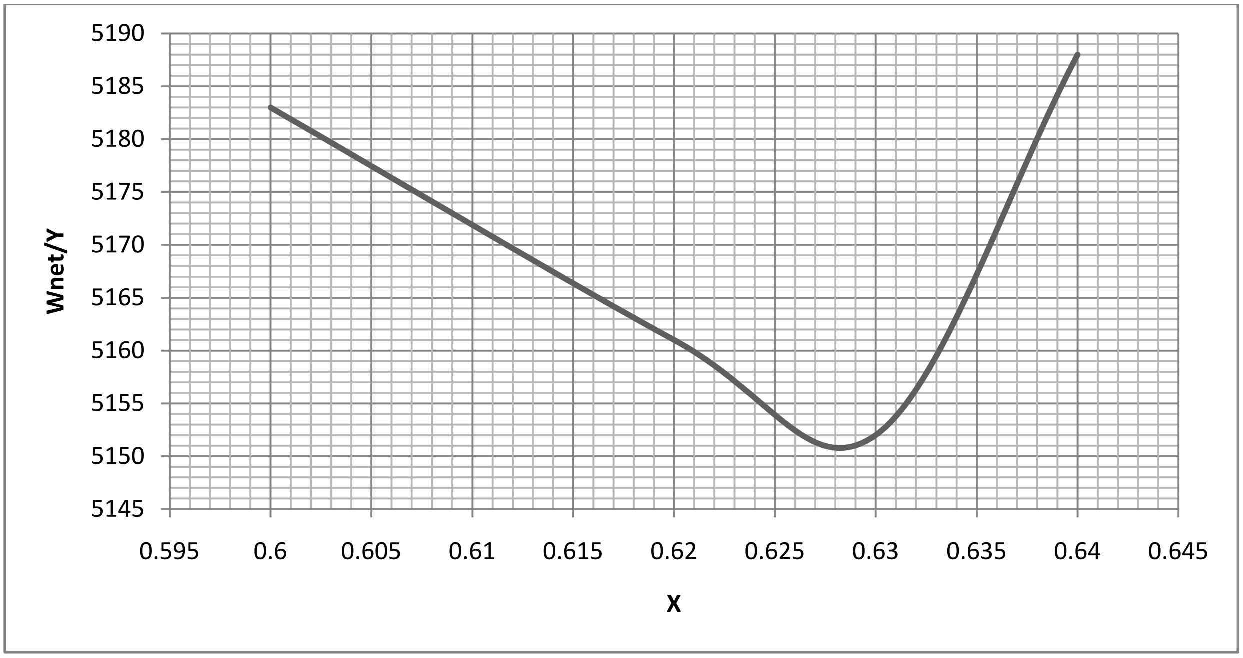


Fig: 4.14 Optimum work required liquefying a unit mass of nitrogen in the Haylent system

Chapter: 5

Simulation of LN2 liquefication plant at NIT-Rourkela

5.1 LN2 plant at NIT-Rourkela

A future plan at cryogenic centre at NIT-Rourkela is to setup a second nitrogen liquefication plant which produce liquid nitrogen whose working principal is based on Kapitza cycle.

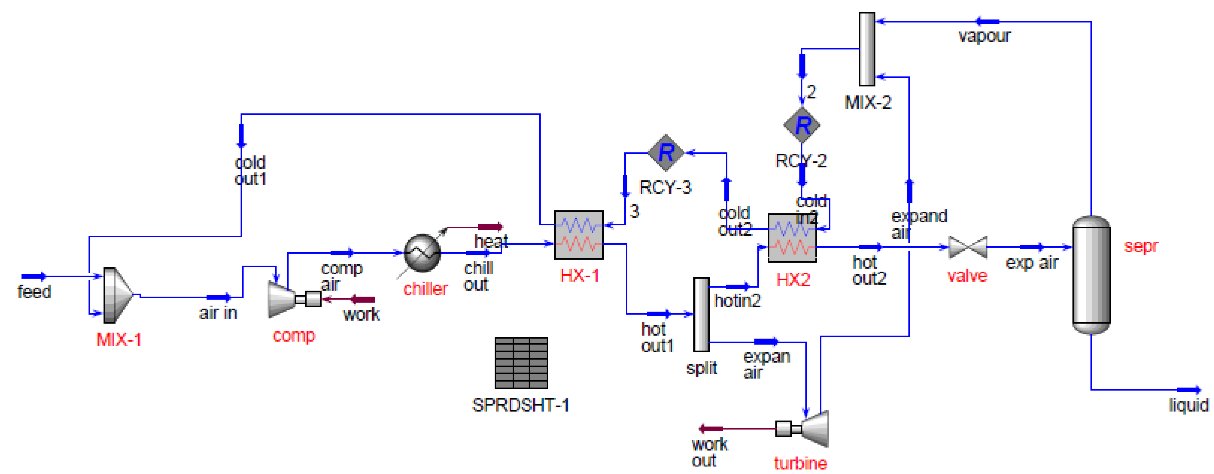


Fig: 5.1 LN2 plant PFD

Simulation of LN2 system

<u>Problem specification</u>:

To solve LN2 system, (using ASPEN-HYSYS) as simulation tool to find the value of x where minimum work required to liquefy a unit mass of nitrogen

Given condition:

$T_{ambient}$ = 310K, $P_{ambient}$ = 1.1 bar,

P_{max} = 8 bar,

Effectiveness of HX1= 0.9, 0.95, 0.97, 0.98, 1.0

Minimum temperature approach in HX_2= 0.5K, 1.0K, 2.0K

Pressure drop in heat exchange is 0.1 bars in each stream is zero

Fluid package = BWRS

Fluid = pure nitrogen

Efficiency of turbine = 40 %, 50 %, 60 %, 70 %, 100 %

S.No	$\eta_{turbine}$	ε HX1	ΔT HX2	Yield (Kg/s)	W_{comp}/Y	% of yeild	Kwh/lit
1	40	100	0.5	4.16E-03	8662	3.99	19.17
2	40	100	1	4.08E-03	8822	3.915	19.52
3	40	100	2	4.11E-03	8766	3.944	19.39
4	40	98	0.5	3.21E-03	10765	3.08	23.82
5	40	98	1	3.23E-03	10987	3.099	24.31
6	40	98	2	3.20E-03	11101	3.071	24.56
7	40	97	0.5	2.80E-03	12612	2.687	27.91
8	40	97	1	2.78E-03	12679	2.667	28.05
9	40	97	2	2.81E-03	12578	2.686	27.83
10	40	95	0.5	1.95E-03	17861	1.871	39.52
11	40	95	1	1.92E-03	18185	1.369	40.24
12	40	95	2	1.91E-03	18222	1.362	40.32
13	40	90	0.5	0	0	0	0
14	40	90	1	0	0	0	0
15	40	90	2	0	0	0	0
16	50	100	0.5	5.22E-03	6898	3.723	15.26
17	50	100	1	5.17E-03	6965	3.687	15.41
18	50	100	2	5.15E-03	6989	3.673	15.46
19	50	98	0.5	4.36E-03	8257	3.1098	18.27
20	50	98	1	4.33E-03	8202	3.088	18.15
21	50	98	2	4.31E-03	8242	3.074	18.24
22	50	97	0.5	3.95E-03	8935	2.817	19.77
23	50	97	1	3.93E-03	8997	3.771	19.91
24	50	97	2	3.91E-03	9037	3.752	19.99
25	50	95	0.5	3.15E-03	11057	3.023	24.47

S.No	$\eta_{turbine}$	ε HX1	ΔT HX2	yield (Kg/s)	W_{comp}/Y	% of yeild	Kwh/lit
26	50	95	1	3.08E-03	11305	2.955	25.01
27	50	95	2	3.06E-03	11393	2.936	25.21
28	50	90	0.5	1.00E-03	33522	0.959	74.18
29	50	90	1	9.48E-04	35508	0.909	78.18
30	50	90	2	8.57E-04	39265	0.822	86.89
31	60	100	0.5	6.31E-03	5707	6.055	12.62
32	60	100	1	6.29E-03	5720	6.036	12.65
33	60	100	2	6.23E-03	5778	5.978	12.78
34	60	98	0.5	5.49E-03	6477	5.268	14.33
35	60	98	1	5.46E-03	6515	5.239	14.41
36	60	98	2	5.39E-03	6589	5.182	14.58
37	60	97	0.5	5.12E-03	6899	4.93	15.26
38	60	97	1	5.11E-03	6911	4.9	15.29
39	60	97	2	5.04E-03	7012	4.836	15.51
40	60	95	0.5	4.29E-03	8067	4.117	17.85
41	60	95	1	4.27E-03	8134	4.097	18.00
42	60	95	2	4.24E-03	8226	4.069	18.2
43	60	90	0.5	2.31E-03	14588	2.21	32.28
44	60	90	1	2.30E-03	14652	2.2	32.42
45	60	90	2	2.24E-03	15038	2.149	33.28
46	70	100	0.5	7.43E-03	4843	7.13	10.71
47	70	100	1	7.40E-03	4865	7.1	10.76
48	70	100	2	7.33E-03	4910	7.034	10.86
49	70	98	0.5	6.65E-03	5345	6.381	11.82
50	70	98	1	6.61E-03	5377	6.343	11.89

S.No	$\eta_{turbine}$	ε HX1	ΔT HX2	yield (Kg/s)	W_{comp}/Y	% of yeild	Kwh/lit
51	70	98	2	6.55E-03	5434	6.285	12.02
52	70	97	0.5	6.34E-03	5577	6.084	12.34
53	70	97	1	6.22E-03	5678	5.969	12.56
54	70	97	2	6.21E-03	5692	5.959	12.59
55	70	95	0.5	5.55E-03	6288	5.32	13.91
56	70	95	1	5.51E-03	6332	5.287	14.01
57	70	95	2	5.41E-03	6446	5.191	14.26
58	70	90	0.5	3.70E-03	9129	3.55	20.20
59	70	90	1	3.60E-03	9366	3.454	20.72
60	70	90	2	3.43E-03	9558	3.291	21.15
61	100	100	0.5	1.11E-02	3248	10.65	7.18
62	100	100	1	1.10E-02	3271	10.55	7.23
63	100	100	2	1.09E-02	3312	10.46	7.33
64	100	98	0.5	1.04E-02	3407	9.98	7.53
65	100	98	1	1.04E-02	3426	9.98	7.58
66	100	98	2	1.01E-02	3510	9.692	7.76
67	100	97	0.5	1.02E-02	3475	9.788	7.69
68	100	97	1	1.01E-02	3509	9.692	7.76
69	100	97	2	9.99E-03	3542	9.587	7.83
70	100	95	0.5	9.47E-03	3692	9.088	8.17
71	100	95	1	9.50E-03	3678	9.11	8.14
72	100	95	2	9.40E-03	3719	9.021	8.23
73	100	90	0.5	7.99E-03	4241	7.667	9.38
74	100	90	1	7.91E-03	4282	7.591	9.47
75	100	90	2	7.77E-03	4356	7.456	9.63

Table: 5.1 Optimum work required at various combination of efficiency of turbine, minimum approach and effectiveness of heat exchange of LN2 plant

Chapter: 6

Conclusion

Conclusion

The above project work presents a cycle simulation for the Nitrogen liquefaction cycle with a compressor, heat exchanger and a J-T valve. It gives us the design data in terms of nodal temperature across the heat exchanger, compressor, chiller etc. and mass flow rates through all the equipments. The above simulation work for Claude's liquefaction cycle for Nitrogen eliminate time and cost expenditure by successfully proven that for low working pressure for Claude system it is useless to use last or low temperature heat exchanger as well as for high working pressure of Claude cycle first heat exchanger is worth. The simulation can be adapted to bring about any changes in the configuration of the liquefaction cycle and can be successfully applied for other complicated cycle.

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